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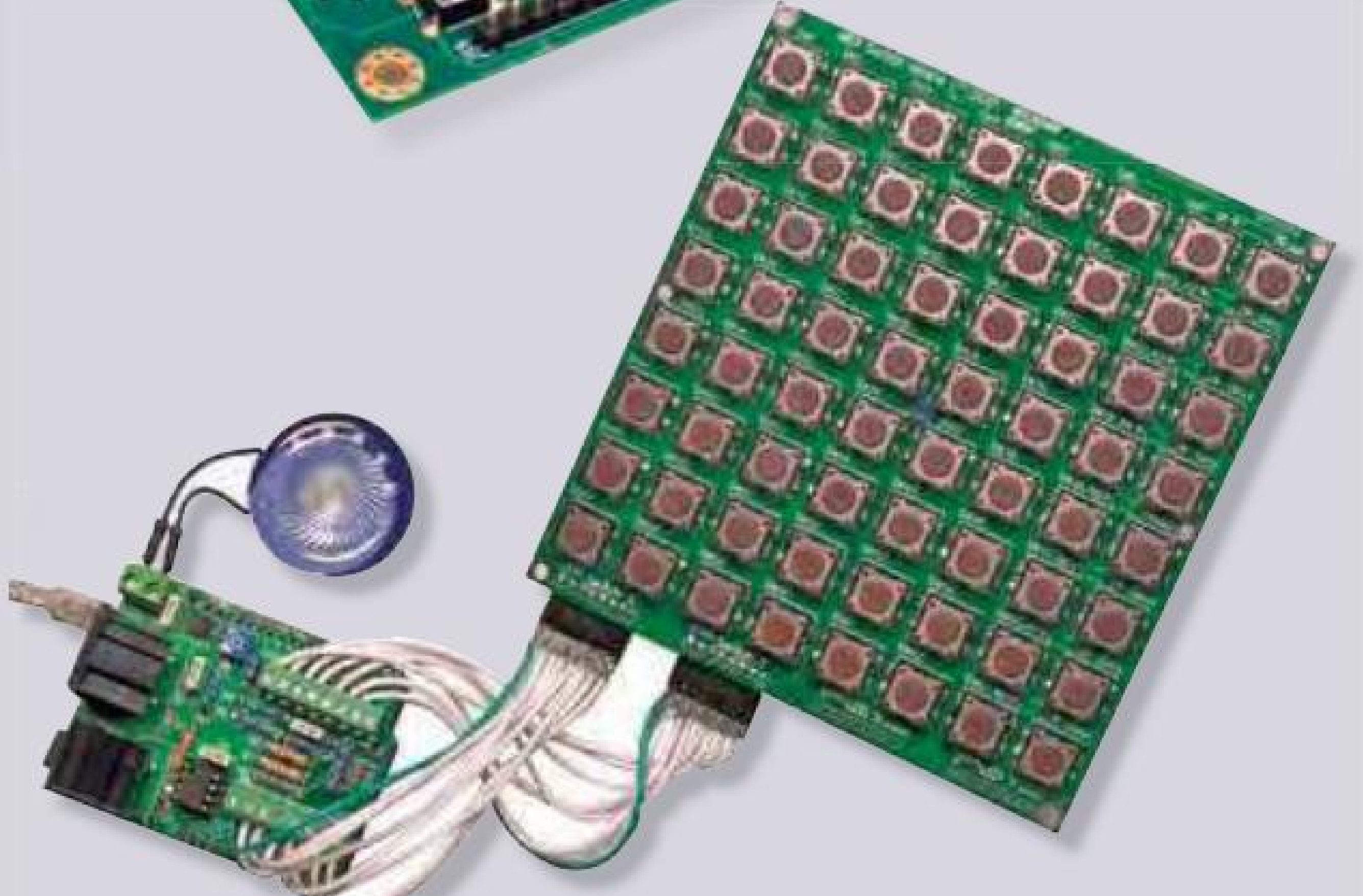

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The June 2022 issue of *Practical Electronics* will be published on Thursday, 5 May 2022 – see page 72.

WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

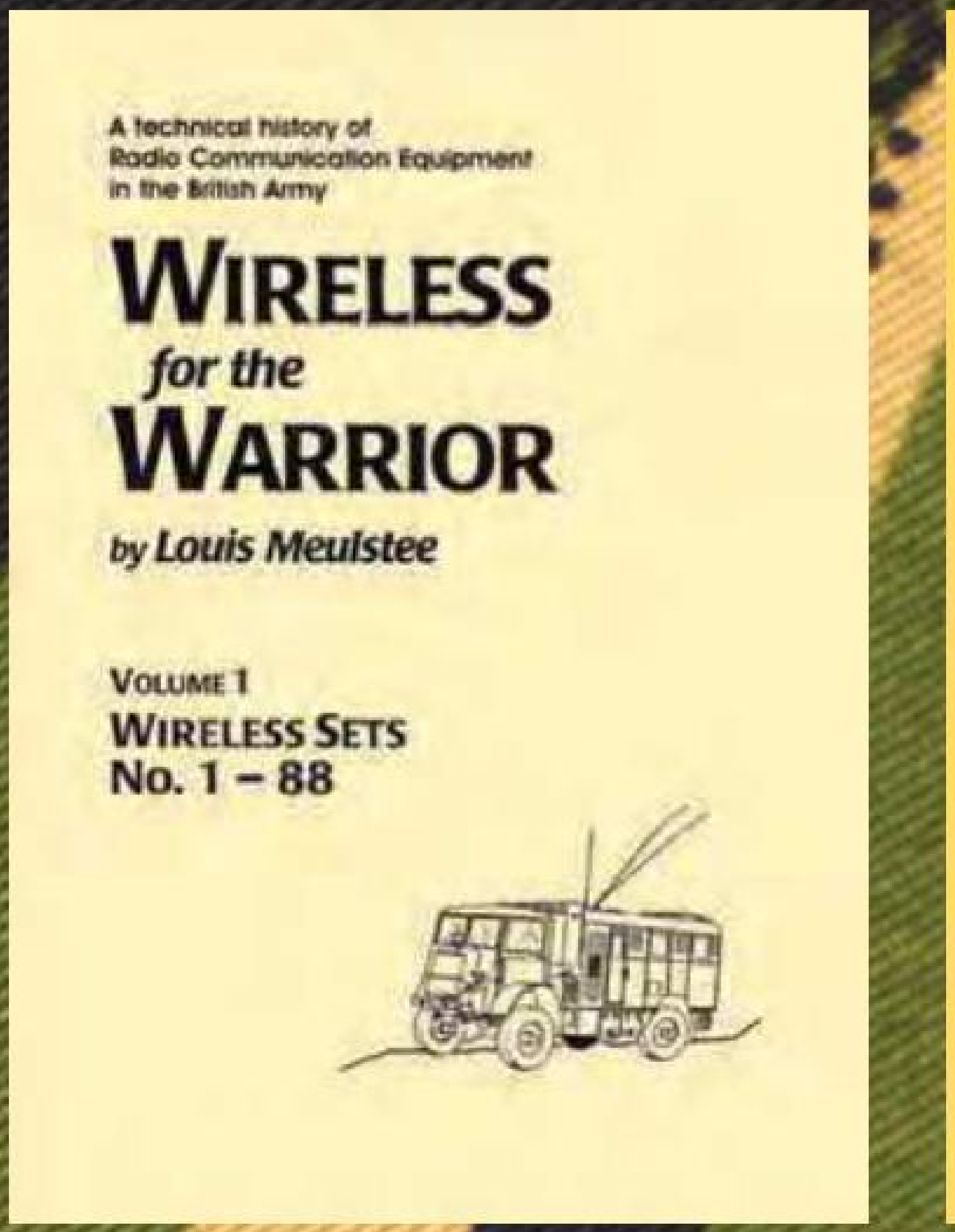
The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

The books are very detailed and include circuit diagrams, technical specifications and alignment data, technical development history, complete station lists and vehicle fitting instructions.

Volume 1 and *Volume 2* cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this timeframe saw the introduction of VHF FM and hermetically sealed equipment.

Volume 3 covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.

Volume 4 covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.



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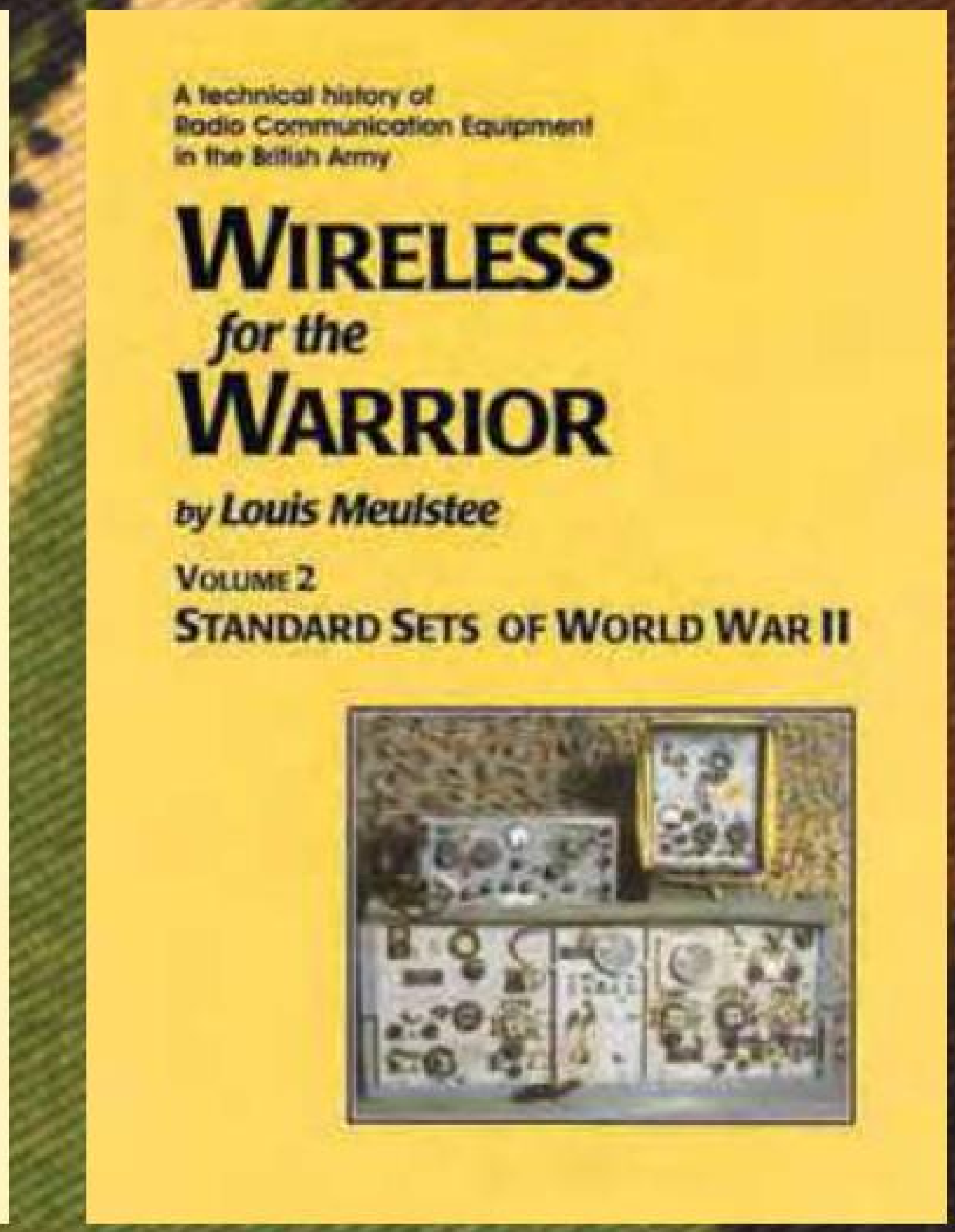

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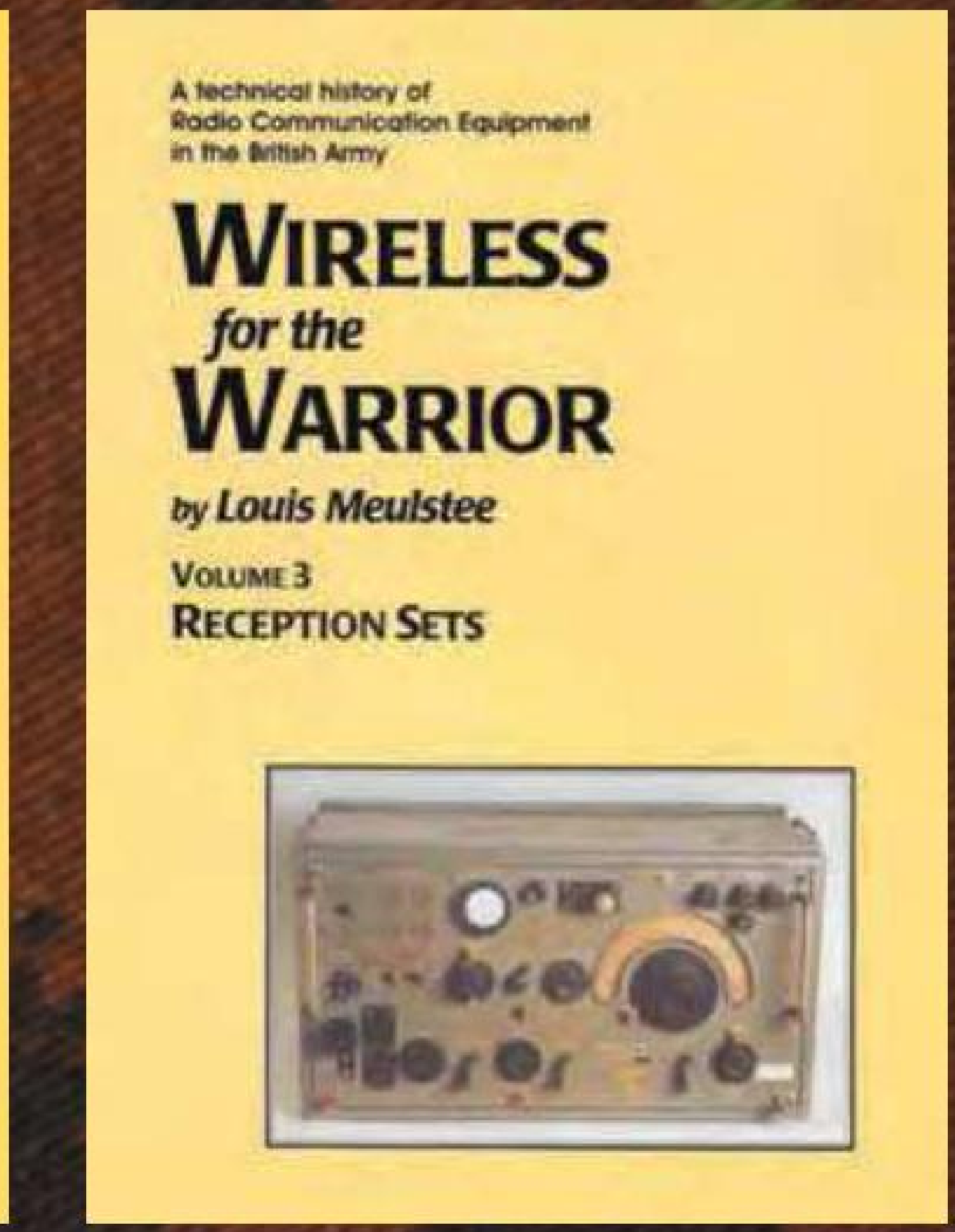

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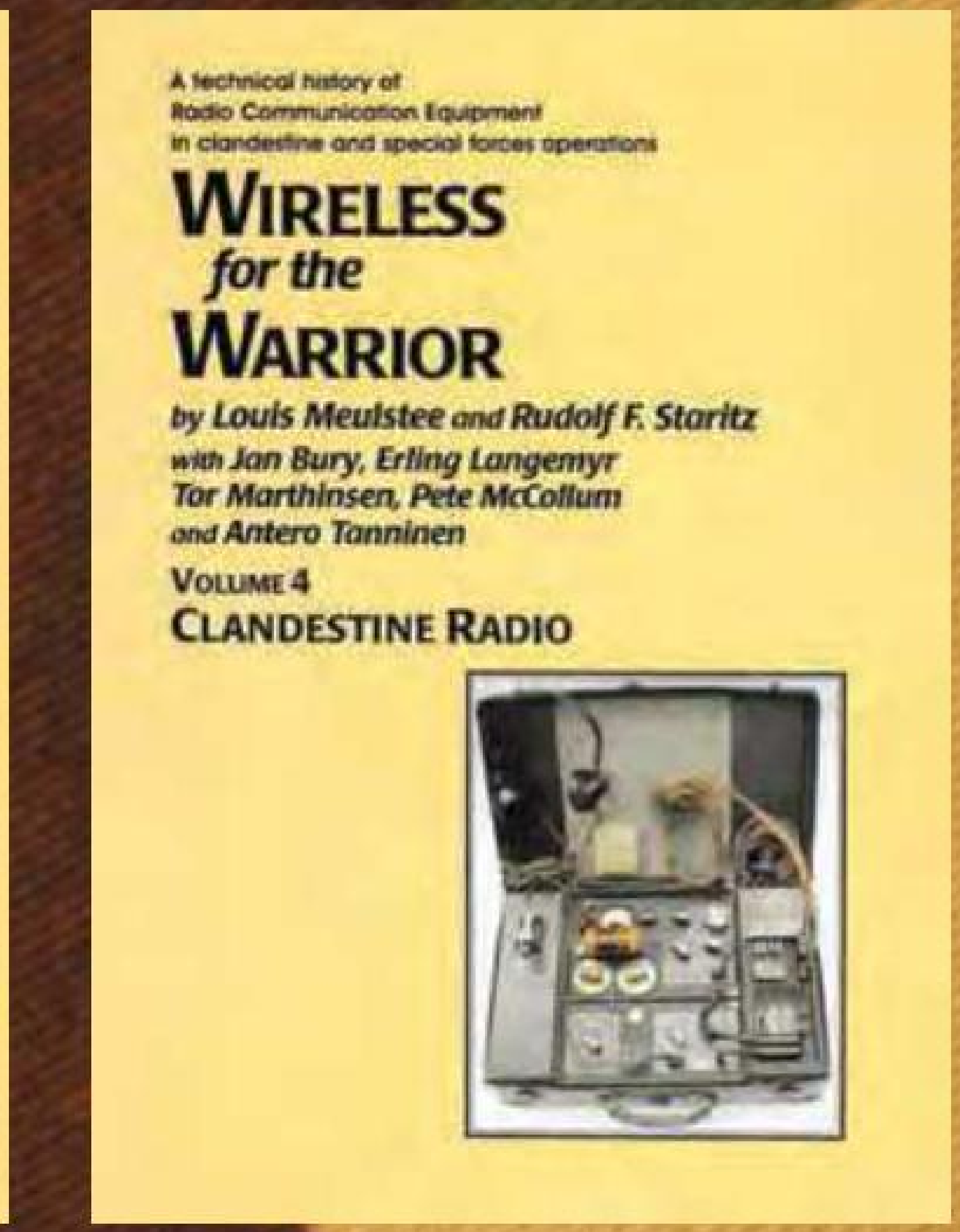

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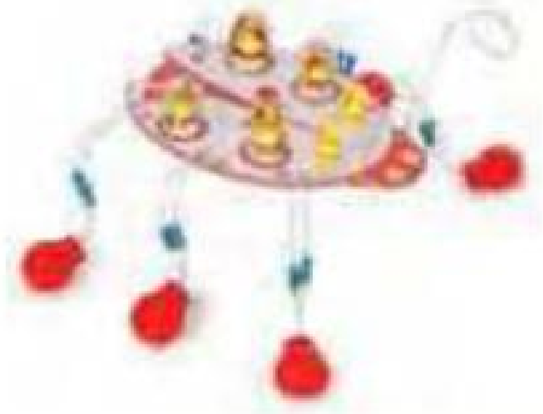

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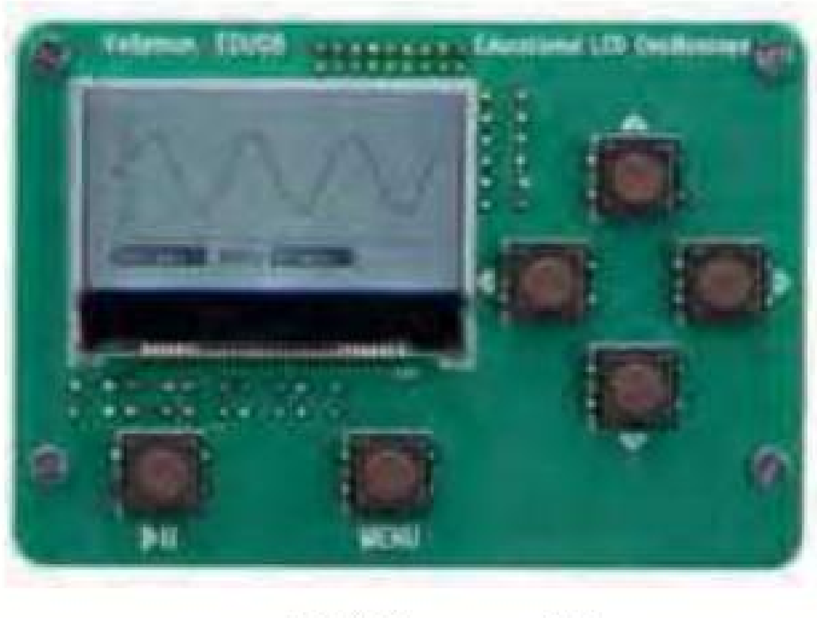

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Fancy an analogue challenge?

These days, it's rare to find a purely analogue project as large and as interesting as Jake Rothman's *Analogue Vocoder*, which concludes this month. Pretty much every design we cover has a PIC, an LCD or some kind of digital component, but not Jake's magnificent *Vocoder* – it really is strictly analogue.

Audio might not be everyone's cup of tea, but it is certainly a wonderful way to learn electronics and has the great advantage of offering something for all levels of ability and experience – from the simplest amplifier to the most esoteric levels of high fidelity. So, even if you're not quite ready to build this challenging project, it's well worth exploring the design over recent issues. Filters, power supplies and amplifiers are basic building blocks that go into many projects and there is much to be learnt from Jake's hands-on approach to practical design.

For those of you who do want to take up the challenge, all the PCBs are now available from the *PE PCB Servic*e. You can buy them individually and build one board at a time, or you can buy the full set at a discount of 30%.

If you do build the *Vocoder*, we'd enjoy hearing your thoughts and feedback.

Digital FX project

Next, we move on to an extremely digital project – the *Digital FX Unit* – which also concludes this month. The difficulty of programming the EEPROM has been raised by a few readers, so we have for sale a few of this IC preprogrammed (as well as the project's accompanying PIC). Please see page 25 for full details.

Unusual oscillator

One column that I especially enjoyed this month is *Circuit Surgery*. Ian Bell's topic for this issue is the 'Royer Oscillator', a design I'd not heard of before. It's a simple, but clever and elegant arrangement based around a transformer. Have a read or better still, have a play with the LTspice files provided by Ian, and available for download from the May 2022 page of the *PE* website.

Lots to keep you busy!

Keep well and stay healthy

Matt Pulzer
Publisher

From nano to bio

Techno Talk

Mark Nelson

Tiny nanogenerators embedded in skin-worn patches and activated by body movement alone can generate electrical fields to accelerate the healing of wounds. And while plant-based foods are just starting to replace meat and cows' milk, it turns out that plant-based plastics have been supplanting their petrochemical-based equivalents for several decades. It's all go in electronics!

The only thing nastier than a body wound has to be a slow-healing or totally stalled wound. I know this from personal experience. But what I didn't know until I researched this article is that electrical fields can speed the process of cell and tissue growth and repair when 'kick-started' by gentle electrical stimulation. Although the technique has been known for decades, the apparatus used was bulky and expensive. However, this has spurred a huge global research effort to reduce size and cost – for example, the British-made Accel-Heal Solo device (**www.accelheal.com/accel-heal-solo/**). Ingenious as this device is, it suffers from the use of body-worn batteries that need to be changed every two days. Therefore, the race is on to develop small, wearable and inexpensive skin patches that aren't encumbered by external electrical equipment.

Nanogenerators

Someone who hopes to find the perfect solution is bioengineer Zong-Hong Lin of the National Tsing Hua University in Taiwan. His research team is working to perfect tiny electric generators to bring wearable, electric, wound-healing devices to clinical practice, avoiding the need for batteries. Some nanogenerators employ synthetic materials such as quartz analogues, ceramics and polymers to generate an electric current when exposed to mechanical stress.

Another device, called a 'triboelectric nanogenerator' (TENG), produces an electric potential when two interfacing materials come in and out of contact with each other (eg, rubbed). Scientists have experimented with TENGs that generate electricity from breathing movements, for example, to accelerate wound healing in rats. They have also loaded TENG patches with antibiotics to facilitate wound healing by also treating localised infection.

'Piezoelectric and triboelectric nanogenerators are excellent candidates for self-assisted wound healing due to their light weight, flexibility, elasticity and biocompatibility,' declares Lin. 'But there are still several bottlenecks.'

For example, they still need to be customised since wound dimensions vary widely. They also need to be firmly attached without being degraded or corroded by the wound environment.

'Our future aim is to develop cost-effective and highly efficient wound dressing systems for practical clinical applications,' concludes Lin.

Two different products sharing exactly the same sales pitch

Sounds confusing? Well, yes, and dodgy too. It involves a highly suspect remedy for sluggish broadband, and if you like having your intelligence insulted with crazy techno-nonsense, you'll love this.

Take a look at **https://getwifiblast.com/blog/wifi-livuk.php** and then read **http://wifi-upgrade.com**. How a Wi-Fi extender can cure bandwidth throttling I just cannot figure. The 'eminent university professor of computer science', Richard Stalworth PhD, who gives the erudite explanation about 'keeping the hose open' all the time to give you internet at full speed is untraceable to any university.

But leaving that aside, does the product work? Sadly not. According to Trustpilot, 92% of customers think it's utter rubbish (**https://uk.trustpilot.com/review/wifiblast.com**). Customers complain about receiving products with two-prongs that do not plug into their mains outlet and a refusal to give any refund. One irate buyer writes: 'The internet speed is slower with the Wi-Fi extender than without and it does nothing to improve the dead spots in the house. I believe there is more than one specification of the extender. What they advertise is the 1,200Mbps specification, but what I received is the 300Mbps specification. Considering my broadband has 1,000Mbps download speeds (tested!), the 300Mbps specification just doesn't cut it.'

Just Google the two words 'Wifiblast' and 'Scam' together; you will take less than 60 seconds to reach a conclusion!

Plant based

Finally, a follow-up to last month's tales of eco and ethical electronics. It's about bioplastics for electronics and provides an interesting slant on where things are headed. This is because it's not just active and passive components that go into electronic products; most merchandise also involves a chassis, an enclosure and much more. These ancillaries often involve the use of plastics and most plastics are derived from increasingly expensive petrochemicals.

But pause for a moment; are there alternative plastic materials? Yes, you can use bioplastics made sustainably from 50% to 100% renewable plant-based ingredients such as corn starch, sugar and vegetable oils, alongside cellulose from waste offcuts of cotton or wood. Using renewable raw materials helps conserve the world's limited (and geographically restricted) supply of petroleum and reduces CO_2 emissions on average when compared to conventional petroleum-based raw materials.

Bioplastics are a good option for long-lasting products, ensuring a positive environmental impact. At the same time, these plastics are just as sturdy, durable, and recyclable as conventional plastics. Even better, bioplastic mouldings that have reached the end of their lifecycle can be 're-granulated' into plastic material that does not have to be made afresh, further conserving resources and energy.

Is it all good news?

Almost, says K&M, a firm that has been using bioplastics in equipment for the broadcast, music and home studio industries for several decades. Its bio-based plastics are just as sturdy and durable as petrochemical-based materials. The shift to bio-based plastics does, however, require extensive (and expensive) development work, and not all bio-based plastics have the properties required for some products. Also, not all bio-based plastics are automatically biodegradable. Long-lasting products that are expected to remain in use under all climatic conditions for years cannot be made biodegradable or compostable using current technologies. Overall, however, the range of products that can be made from bioplastics is growing constantly, as is the industrial adoption of this material.

Exclusive offer

Win a Microchip Explorer 8 Development Kit

Practical Electronics is offering its readers the chance to win a Microchip Explorer 8 Development Kit (DM160228) – and even if you don't win, receive a 15%-off voucher, plus free shipping for one of these products.

The Explorer 8 Development Kit is a full-featured development board and platform for 8-bit PIC microcontrollers (MCUs). This kit is a versatile development solution, featuring several options for external sensors, off-board communication and human interface. Additionally, it offers ample room for expansion, making it an excellent solution for developers and engineers looking for a tool with the largest number of supported 8-bit PIC MCUs.

The Explorer 8 Development Kit is the latest offering in a long line of enterprise-class tools for 8-bit PIC MCUs. The board is an evolution of the popular PIC18 Explorer Board, and has been updated to take advantage of our most modern features, including:

- On-chip Core Independent Peripherals
- Compatibility with all PIC MCUs
- 8-, 14-, 20-, 28-, 40/44-, 64- and 80-pin footprints.

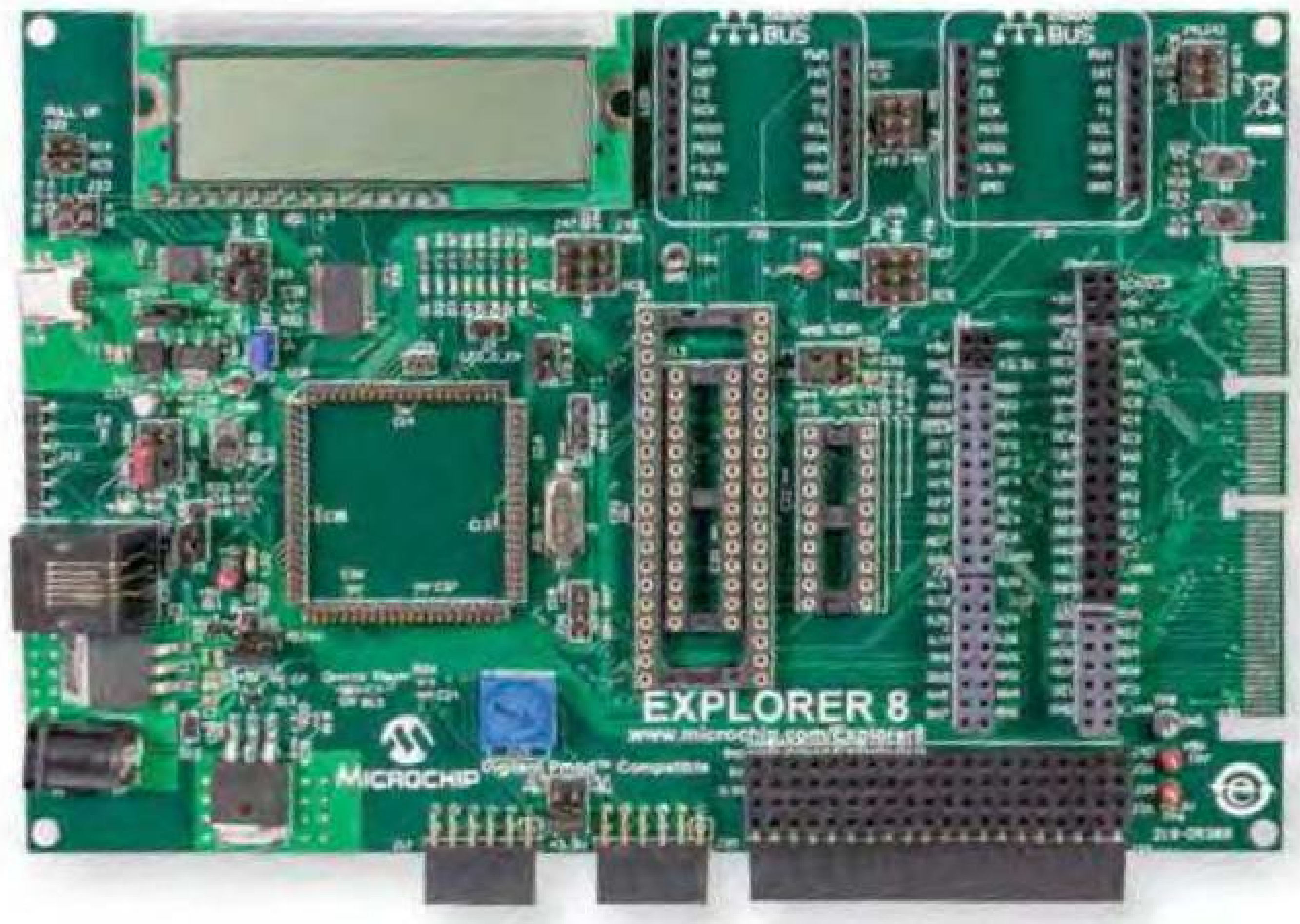
With the Explorer 8 Development Kit, you can have a single development platform that allows you to update a legacy design while supporting our newest MCU offerings.

Microchip designed the Explorer 8 Development Kit to be your main tool for 8-bit development with support for a wide variety of functions. On-board components enable easy development of human interface, power conversion, Internet of Things (IoT), battery charging and other applications using a powerful 8-bit PIC MCU.

Additionally, the Explorer 8 Development Kit also has a large capacity for expansion. Two Diligent Pmod interfaces, two MikroElectronika Click board sockets and two custom expansion headers allow you to quickly adapt as your development needs change. The Explorer 8 Development Kit supports several program and debug solutions, including the PICkit 3, ICD 3 and MPLAB REAL ICE In-Circuit Emulator.

Worth $107.79 (approx £79.50) each

Free-to-enter competition



Microchip Explorer 8 Development Kit

How to enter

For your chance to win a Microchip Explorer 8 Development Kit or receive a 15%-off voucher, including free shipping, enter your details in the online entry form at:

https://page.microchip.com/PE-Exp-8.html

Closing date

The closing date for this offer is 30 April 2022.

January 2022 winner

Jeff Erwin

Digital Power Starter Kit
BUCK
BOOST

He won a Microchip MPLAB Starter Kit for Digital Power

Net Work

Alan Winstanley

Welcome to this month's *Net Work*, bringing you a round-up of topical technological issues and trends from the UK and around the world.

With major spikes in the price of wholesale energy heading our way, British energy consumers are already facing swingeing increases as the six-monthly energy 'price cap' is due to rise very shortly. (How the UK price cap review works is explained by Ofgem here: **https://tinyurl.com/mry964ah**) Analysts have predicted a rise of over 50%, with a further 20% possibly in October. However, with world events unfolding before our very eyes, energy supplies are being upended once again, and the focus on energy diversification will doubtless be accelerated as supplies of gas gradually unravel. The major new Nordstream 2 gas pipeline has been shelved by Germany and, ironically, coal, oil and shale gas are now being actively re-considered to plug the gap and cushion us against any price rises. Liquefied natural gas (LNG), delivered by bulk tanker ships, is another option and even nuclear power stations may be revitalised in Germany. The small modular (nuclear) reactor rollout across eastern Europe, described in earlier columns, seems less certain now, although American SMR maker NuScale recently signed a deal to build one in Poland.

In Britain, the shockingly expensive (£11bn) smart meter rollout continues, with consumers being urged to 'do their bit' and help 'modernise' the gas and electricity networks and also streamline the job of taking meter readings. The latter feature is sold as a benign benefit of smart meters, since they will be able to 'phone home' with meter readings every day, or even every 30 minutes, starting in 2025. As I wrote over two years ago, smart meters will ultimately change the way we manage and pay for our power consumption. Eventually, discounts or surcharges will be levied depending on the time of day, weather conditions and most of all, the availability of energy supplies to begin with. It is to be hoped that an increase in wind power (offshore, and now onshore), LNG and maybe utilising more of Britain's own abandoned resources will help to keep the lights on, if not the central heating.

The Giga economy

Although every major car manufacturer has committed to building emissions-free EVs, there is still plenty of life left in petrol and diesel cars. Owners of EVs fret about their car's range and they top up en route at service stations with, say, '100 miles worth' of charge – assuming they can find a compatible charging point that works properly. The high price of EVs and spartan charging network are two major deterrents for car buyers, and that's before we consider whether power generators or battery producers will even be able to meet spiralling demand.

So-called 'gigafactories' are springing up that are dedicated to the mass production of batteries and electric vehicles. Tesla's planned gigafactory near Berlin had been stalled due to environmental hurdles, but is finally heading towards production, a year late. Tesla already has an overseas gigafactory in China. UK battery maker Britishvolt (**www.britishvolt.com**) has announced a battery gigafactory of its own in Northumberland, north-east England. The site will use plentiful supplies of local renewable energy and has attracted over £1.8bn ($2.3bn) of investment funding. Britishvolt is also partnering with commodity trader Glencore to build a battery recycling facility capable of handling 10 kilotonnes of waste a year. Outline planning permission is also expected for the new 'West Midlands Gigafactory', a public-private venture between Coventry City Council and Coventry Airport in the heart of England. They claim the £2.5bn ($3.25bn) investment will be the largest battery gigafactory in the UK, with production expected to start in 2025.

The Anglo-Korean 'next-generation' battery company Eurocell aims to build its first European-based gigafactory too, turning out 'production-ready' batteries in just 12 months from a standing start, far quicker than other gigafactories will be able to, they claim. An initial £600m ($0.78bn) investment is planned over two phases, and the company intends to supply products for European energy storage, automotive, and e-mobility applications. Eurocell is considering sites in the UK, the Netherlands or Spain, dependent on government support offered;

Britishvolt has announced a new battery gigafactory in Northumberland, England, at a cost of over £1.8bn of investment funding.

widerøe
TECNAM P-VOLT
LN-SNO

Rolls-Royce is partnering with Scandinavian regional airline Widerøe and hopes to launch an all-electric commuter plane in 2026.

possibly Britain offers the added attraction of operating outside of EU strictures. The new site would reach full production by 2025. More details at: **https://eurocell-emea.com**

Meanwhile, StoreDot, the Israeli manufacturer exploring XFC (Extreme Fast Charge) batteries mentioned in the March column, has launched its '100inX' road map outlining the likely charge time their batteries hope to achieve to yield a range of 100 miles. StoreDot expect to offer EV batteries with a charge rate of [up to] 100 miles range for five minutes of charge time by 2024, with 100 miles in two minutes as their target in a decade's time. '100in5' cells are already being evaluated by several EV manufacturers, they tell me.

More EV projects that are breaking cover include the all-new Fisker Ocean electric SUV which debuted at Mobile World Congress in Barcelona. The California-based start-up expects to start production by the end of 2022, and they see the European market as critical for its success. Solar cells in the 'SolarSky' roof supplement the electric motor and the vehicle will be built using a large amount of recycled material to enhance its 'green' credentials. Readers can take an early look at: **www.fiskerinc.com**

In the March column I mentioned that the Japanese consumer giant Sony had surprised the EV sector by revealing a second prototype electric car at this year's Consumer Electronics Show. Sony's Vision S-02 EV was presumed to be a pre-production testbed for mobile sensors and electronics, but Sony has now inked a deal with none other than Honda. The aim is to 'create a new era of mobility and mobility services', says Honda, with production of their first car expected in 2025.

Taking flight

Following my item last month on the Autoflight eVTOL 'Prosperity 1' all-electric flying taxi, the makers report that the craft has achieved its first 'transition flight': shifting from vertical take-off to forward motion and back again. The three-passenger-plus-pilot aircraft has eight vertical props and two horizontal ones, and you can witness the test flight at: **https://youtu.be/QPqFCJC7ozs**

Rolls-Royce hopes to launch an all-electric passenger plane in 2026. Partnering with Widerøe, Scandinavia's largest regional airline, the all-electric passenger aircraft would be a perfect solution for providing emissions-free commuting between the area's multitude of regional airports.

Back to earth, and the practicalities of charging EVs themselves – the UK's National Grid reckons that 75% of EV owners who can charge at home, will continue doing so. To give our needy electricity network a boost, one option being considered is to use an electric vehicle's batteries to sell surplus energy back to the National Grid, paying EV owners for the privilege (domestic solar-panel style). This emerging technology is called Vehicle-to-Grid or V2G. As predicted, Time of Use Tariffs (ToUT) could be introduced to supposedly 'incentivise' owners to charge overnight at off-peak times; put another way, owners could face surcharges for using electricity at peak times. An interesting summary of V2G is online at: **https://bit.ly/pe-may22-v2g**

Also waiting in the wings is the idea of using an EV's battery to top up the homeowner's own domestic electricity supply. Vehicle-to-Home (V2H) bidirectional chargers are being explored by UK charger manufacturer Indra, which admits that the technology is not yet commercially available. The smart chargers would also receive remote OTA (over the air) updates.

First outlined in January's column, the ZipCharge Go 'powerbank on wheels' for EVs is now at an advanced validation prototype and procurement stage, the makers tell me. Some 40% of car-owning households have no designated or off-street parking, ZipCharge says, so the portable electric charger may be one

The new Fisker Ocean electric SUV claims to have the longest range in the segment, and production is due to start in late 2022.

The ZipchargeGo powerbank for EVs is due to launch in 2023

A prototype Scania electric truck charging during motorway trials in Germany. A 20km trial is being considered in the UK. (Image: Tom Scott/ Youtube)

answer to topping up an EV overnight. The ZipCharge Go contains various anti-theft and security features and is slated to launch early in 2023.

It's starting to become clear how car ownership and travel will take shape in years to come as we gradually move away from petrol and diesel fuels. Owners of electric vehicles in Britain might be able to mitigate some energy price rises by switching to an EV-aware tariff that offers cheaper overnight charging rates (smart domestic electric appliances of the future will do the same, automatically). The Rightcharge charge-point and EV tariff comparison website reckons that savings can be made by EV owners who switch this way. Charlie Cook, founder of the Rightcharge website, said: 'The cost of standard variable tariffs is about to rocket by 54% from 1 April as Ofgem increases the price cap. By switching from a variable tariff to an EV-friendly tariff, drivers can schedule for overnight charging and reduce their bills by an average of around £300 per year. By doing so they will also be charging on electricity that is roughly 25% cleaner in comparison to electricity consumed during the evening hours.' More resources for EV users are online at: **https://rightcharge.co.uk**

Big battery

Batteries aren't just for electric vehicles, though: Singapore-based Sembcorp, a sustainable energy solutions provider, recently announced that Europe's largest battery energy storage system will be built on Teesside in northern England, to help the UK achieve its 'Net Zero' target. It will be home to a 360MW Li-Ion battery storage system offering several hours of power, and the near-instantly available power boost will help balance out the National Grid's supply lines. (See: **https://bit.ly/pe-may22-sem**) Nearby, a new 300MW natural gas power plant – the Whitetail Clean Energy site (**https://whitetail.energy/**) – could be built by Sembcorp and the zero-emission site will use gas and oxygen, rather than air, for fuel; the turbines would be driven by liquefied carbon dioxide rather than steam. It would capture up to 800,000 tonnes of CO_2 a year for storage under the North Sea.

Keep on (electric) trucking

I mentioned in a previous column that the US truck maker Kenworth recently introduced its first electric lorry. (Ever wondered why European truck cabs are shorter than US or Australian ones? Legal limits on the length of our trucks mean that drivers of European trucks sit 'above' the engine rather than behind it.) The move towards electrifying the transport network is not exclusive to cars or vans (or trains, buses or trams) though: several weeks ago I met a representative of a consortium comprising the civil engineers Costain, Siemens, European truck maker Scania, overhead line equipment (OHLE) engineers SPL-Powerlines, technical architects Arup, and Cambridge and Heriot Universities. Therein lies a clue: the group hopes to carry out a UK government feasibility study with the objective of removing diesel freight trucks from our roads by 2040. A stretch of motorway has been pencilled in to hold the UK's first trial of electric trucks, which if successful would also study freight logistics surrounding one of Britain's largest ports. Electric trucks are already catching on in Sweden, with Volvo Trucks offering a range of vehicles for urban and local deliveries (see: **https://bit.ly/pe-may22-vol**). The British motorway trials would use 20km of overhead lines to power electric trucks running beneath them. Some proofs of concept trials are already running on a 2km stretch in Sweden (for example, see the report: **https://youtu.be/27100u7IcII**) as well as in Germany: **https://youtu.be/_3P_S7pL7Yg**

These prototype trucks would draw overhead power and recharge their batteries using pantographs (so-called 'in-motion charging'), before the vehicle completed the final stretch entirely electrically propelled. There are all sorts of design and economic challenges to overcome, including the fact that motorway bridges will interrupt the catenaries of overhead lines; perhaps cables might go underground in places and trucks will automatically disconnect and reconnect as they pass underneath. It's not yet clear whether such trucks would be 100% electric or a hybrid diesel/electric. The whole business model has yet to be fleshed out and it will be many years before Britain's electric truck infrastructure is built, but it's a sign of things to come.

A magnetic attraction

One component that everyday life depends on is the humble magnet. They are everywhere, from motors to loudspeakers to transducers, and 4,000 tonnes of permanent magnets from defunct gear are produced every year, says minerals miners Pensana plc. The rare earths market is dominated by China and is critical to the production of permanent magnets, and the company is planning a new $190m facility to produce up to 12,500 tonnes annually of rare earth oxides at Saltend, near Hull in England. By 2025 Saltend is expecting to produce 4,500 tonnes of neodymium and praseodymium (Nd/Pr) annually, or over 5% of the world market and will be one of only three such facilities outside of China. The company already owns a state-of-the-art rare earth mining facility in Angola.

It's no co-incidence that the area on the north bank of the River Humber in eastern England, is also becoming a tariff-free Freeport with factories being established nearby to manufacture wind turbines – each of which is said to contain several tonnes of permanent magnets. The industry supplier Goudsmit has more background at: **https://bit.ly/pe-may22-mag**

The UK Government is also investing in the emerging idea of floating offshore 'wind ports' to generate electricity. Some concepts were floated, as it were, by Equinor at: **https://bit.ly/pe-may22-osw**

Workshop whoops...

My thanks to regular *PE* reader Glenn Patterson who dropped me a line: 'I continue to enjoy your monthly column in *Practical Electronics* and I've just read your February 2022 *Net Work* (also noting that magazine subscription deliveries to here in Australia appear to be back on track!) and I was surprised to read that Ryobi Europe has persisted with Ni-MH battery technology in their 18V power tool range.

'While I don't have any Ryobi products, I embraced the Makita 18V Li-ion platform nearly 10 years ago, and have been extremely happy with them – Li-ion being the preferred and more durable battery technology. I also note that Ryobi 18V OnePlus products available from the local Ryobi retail outlet down under (Bunnings here in Australia) is Li-ion based. Again, I look forward to receiving the monthly *PE* magazine, and the regular columns therein. Cheers, Glenn.'

When writing about Ryobi's popular 18V OnePlus battery-powered tools, I inadvertently implied that their NiMH batteries were still on the market. I must clarify that Ryobi of course majors entirely on 18V Li-ion batteries and I even found some of them on the 6-port charger above my own workbench! Thank you for pointing that out, Glenn, and for your regular subscription too! Ryobi 18V OnePlus tools are available from the usual sources and their range of accessories (200+) is expanding all the time. Remember that 'bare tools' don't include batteries or chargers, which must be bought separately.

Also in February's column, I described how my perfectly good first-generation Google Home Hub (now called 'Nest Hub') smart speaker with LCD screen had suddenly locked up last year for no reason at all. Many disgruntled users were found online, complaining about the same problem. Google has been totally tight-lipped about addressing the issue and no one's reported a software fix, but fingers point to firmware problems or some bloody-minded changes in Google's network. Of course, hardware warranties only last typically for one year anyway, and mine was barely two years old before its software was suddenly hobbled. It would appear that unhappy users are expected to toss the things away.

The small print on the defunct Home Hub box (found in the attic) states that Google features and functionality are subject to change 'without notice or obligation', which presumably includes pulling the plug on the device altogether without warning. Google did not answer requests for an explanation.

In comparison, Amazon guarantees their Alexa-powered Echo devices will receive software security updates until at least *four years* after the devices are last made available for purchase. A clear timetable is published at: **https://amzn.to/3Mu5KyE**, which offers users some reassurance about the likely operating lifespan of these smart displays and speakers.

Space news

Finally, nearly 50 years after the Soviet Soyuz and American Apollo capsules docked in space to symbolise friendship and cooperation (see: **https://bit.ly/pe-may22-apsoy**), the space programme has become another tragic casualty of the turmoil in Europe, starting with the UK's OneWeb LEO satellite project. These use Russian-built Soyuz rockets and the next tranche of 36 OneWeb satellites, due to blast off in early March, was duly grounded when the UK Government refused to meet some demands. OneWeb then cancelled launches from the Baikonur Cosmodrome in Kazakhstan, and SpaceX has reportedly offered to launch them instead. Soyuz launches from French Guiana have also been cancelled by Roscosmos – the site where the James Webb telescope was launched last December using an Ariane rocket (see: **https://go.nasa.gov/3MnQqDD**)

Meantime, Elon Musk's SpaceX has launched another 47 Starlink satellites into orbit, where about 1,500 or so are said to be in active operation, with hundreds more manoeuvring into position. SpaceX also delivered a lorry full of Starlink terminals to Ukraine to offer satellite-based communications to the war-torn nation. Recent *Net Work* columns also highlighted Virgin Orbit's latest successes to launch satellites into space quickly and cheaply using a 747 (see last month), which could form a timely shortcut into space. The UK government is also accelerating its promise to enter the space launch sector: the northern-most island of Unst is home to the new SaxaVord Space Port, where it is planning to offer launch services for Europe starting from 2024. A Memorandum of Understanding was reached with the French small launch rocket developer Venture Orbital Systems (VOS). A new ground station array to support satellite operations is also planned there. You can learn more at: **https://saxavord.com**

I'd like to sign off this month by saying that writing a monthly column that won't be published for several weeks can present me with a lot of challenges, especially when trying to remain topical and timely. Not wanting to tempt fate, I am presently left wondering what the world will look like when the printed version finally reaches the newsstands. For what little comfort it will offer, I can say that, today, all our thoughts are with those whose lives have been so terribly affected by the appalling war that is engulfing Ukraine. You can find ways to help through UNICEF, the Red Cross and respected others here: **https://bit.ly/pe-may22-slaukr**

The author can be reached at:
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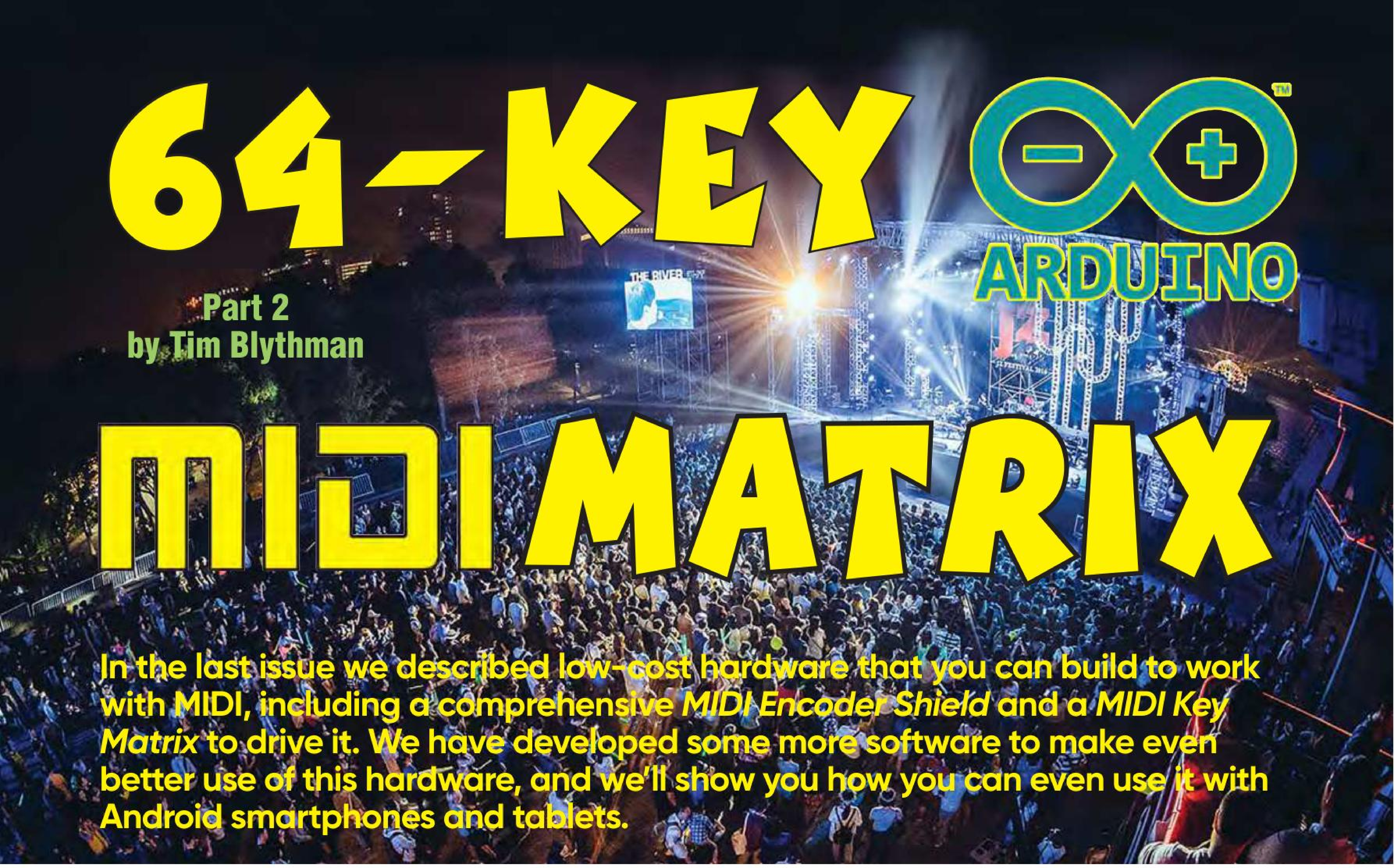


64-KEY ARDUINO

Part 2

by Tim Blythman

MIDI MATRIX

In the last issue we described low-cost hardware that you can build to work with MIDI, including a comprehensive *MIDI Encoder Shield* and a *MIDI Key Matrix* to drive it. We have developed some more software to make even better use of this hardware, and we'll show you how you can even use it with Android smartphones and tablets.

The first part of this series showed how to build a simple *MIDI Key Matrix*, consisting of a grid of 64 tactile switches. These are scanned by an Arduino-compatible Leonardo board, which acts as a *MIDI Encoder*. It uses its USB peripheral to generate MIDI messages which can be received on a personal computer running synthesiser or digital audio workstation (DAW) software.

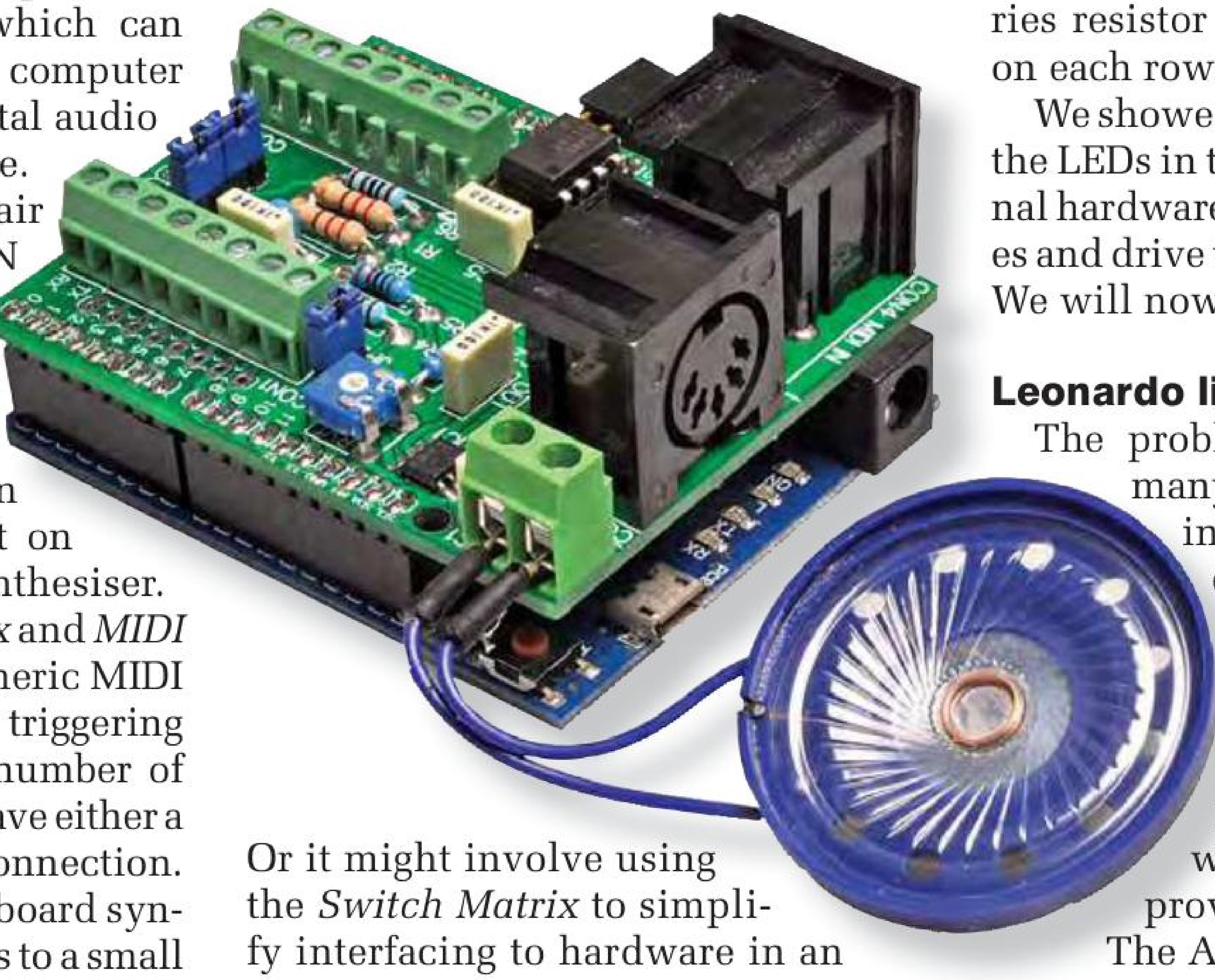
It's also fitted with a pair of MIDI-standard 5-pin DIN sockets. These are configured as MIDI-out and MIDI-in ports. MIDI-out ports generate 'hardware' MIDI messages which can be fed to the MIDI-in port on a device such as a MIDI synthesiser.

Thus, the *MIDI Key Matrix* and *MIDI Encoder* together form a generic MIDI output device, suitable for triggering sounds and notes on any number of MIDI-capable devices that have either a USB or 5-pin DIN MIDI-in connection.

It also has a very basic onboard synthesiser which delivers notes to a small 1W speaker as key events occur. On its own, it forms a very simple musical instrument.

While it's possible to wire up the matrix of 64 keys by hand, we also showed how to build a PCB-based *Switch Matrix*, which simplifies this greatly. The *Switch Matrix* provides support for several differently-sized tactile switches.

We expect some people will think of new and interesting ways to use this hardware. This might include custom programming of the *MIDI Encoder* to perform a specific role in a MIDI setup. Or it might involve using the *Switch Matrix* to simplify interfacing to hardware in an unrelated project.



If you want to know more about MIDI's background and workings, see the 'What is MIDI?' panel on page 19.

LED Matrix

While we intended to create a cheap and useful MIDI input device, we've used the ample space on the *Switch Matrix* PCB to add extra features. In particular, there are pads to allow illuminated switches to be fitted.

These are also connected in matrix fashion back to a pair of 8-way connectors (CON3 and CON4), with a series resistor for LED current limiting on each row.

We showed some basic code to drive the LEDs in the first part, but the original hardware couldn't sense keypresses and drive the LEDs at the same time. We will now address that.

Leonardo limitations

The problem is that there aren't many pins spare on the Arduino Leonardo; certainly not enough to drive the LEDs and scan the switches simultaneously.

Indeed, there aren't many Arduino compatible boards around that would allow that and still provide a USB peripheral.

The Arduino Mega has enough pins, but unfortunately, its USB support is limited to serial data through a separate USB-serial IC.

In the last issue, we noted that if you just want to light up all the LEDs, you can simply connect power rails to CON3 and CON4 on the *Switch Matrix* PCB.

But if you want independent control of the LEDs, the simplest approach is to add a second microcontroller board.

You might want to light up each key as a prompt to indicate which one should be pressed next. This could be handy as a learning tool, helping to learn a musical piece by rote.

Another example would be to light up the LEDs in time with the keys that are being pressed. This is what we've done with our example code.

A tale of two micros

To light up the keys in time with the keypresses requires communication between the two micros, even though we've already established that one of them doesn't have many pins to spare. Our trick is to borrow one that's already being used.

The MIDI specification supports so-called SYSEX (System Exclusive) messages. These messages are intended to allow manufacturers of MIDI equipment to send custom data that doesn't fit into the standard messages. They can be used (for example) to send audio sample data between devices.

Many manufacturers have specific identifiers, but the 0x7D identifier can be used for development purposes, and that's what we're doing here. Using this identifier means our data won't be confused with another manufacturer's signals.

The System Exclusive message that we send consists of a status byte 0xF0, identifier 0x7D, followed by the ASCII codes for 'SC'. These extra characters reduce the chance that the data could be misunderstood by other equipment.

We follow this with any number of data bytes in the range 0x00 to 0x7F, which gives us 128 codes. Codes 0-63 turn off LEDs 0 to 63 respectively, while codes 64-127 turn on one of them.

Any data byte greater than 0x7F (ie, with the most significant bit set) ends the SYSEX message, although we send 0xF7 as this is the defined 'End SYSEX' command. All MIDI equipment understands this, and thus everything remains in sync, ignoring data inside these packets.

We send this data out on the MIDI out port. Most MIDI equipment will ignore these bytes, so it won't interfere with our note messages.

It's then a simple case of receiving that data and displaying it on the LEDs. We're using a second Leonardo board to do this.

Because MIDI data is no more than a serial bitstream at 31,250 baud, we set up a state machine to monitor the incoming data.

Once it has received the bytes 0xF0, 0x7D, 'S' and 'C', it assumes that any following data bytes are commands to turn the LEDs off and on as described above, until it receives a byte above 0x7F, which resets the state machine to wait for the sequence again.

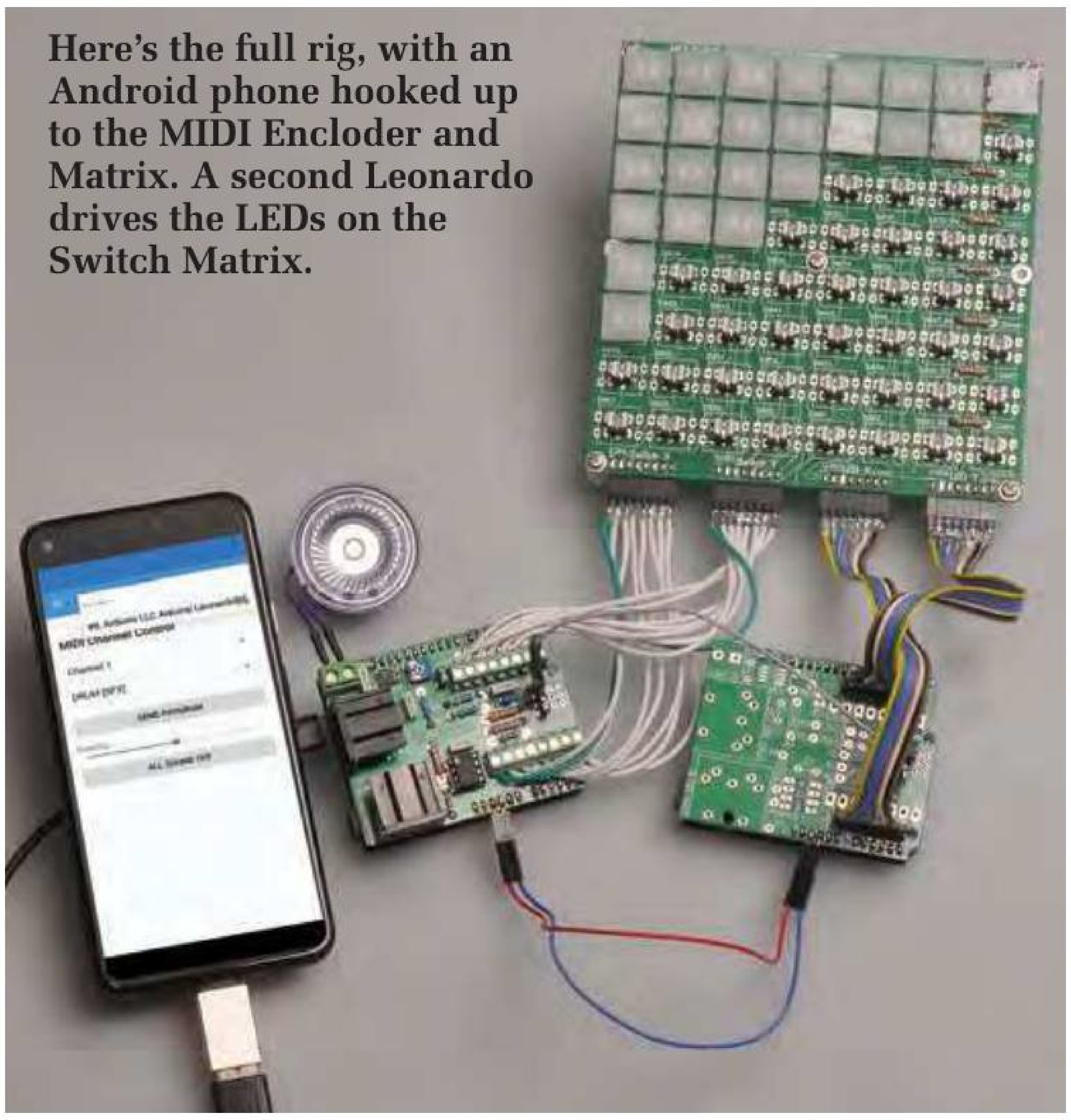
The LEDs are multiplexed by a timer interrupt, which ensures that each column receives an equal amount of time and thus the LEDs are driven with even brightness. The code scans through each column in turn, lighting up the LEDs according to the previously received commands.

LED driving hardware

Since our LED Driver uses standard MIDI packets, the deluxe way to assemble this is to use two Leonardo boards, each topped with a fully kitted-out *MIDI Encoder*.

A standard MIDI cable from the MIDI-out port of the unit programmed as the *MIDI Encoder* is connected to the MIDI-in port of the unit programmed as the LED Driver; each unit is supplied with power via its USB port.

The LED connections on CON3 and CON4 of the *Switch Matrix* are connected to CON2 and CON1 on the MIDI Shield, as described last month in *Part 1*. So the *MIDI Encoder Shield* only needs the MIDI-in, CON1 and CON2 headers to act as the LED Driver.



Here's the full rig, with an Android phone hooked up to the MIDI Encloder and Matrix. A second Leonardo drives the LEDs on the Switch Matrix.

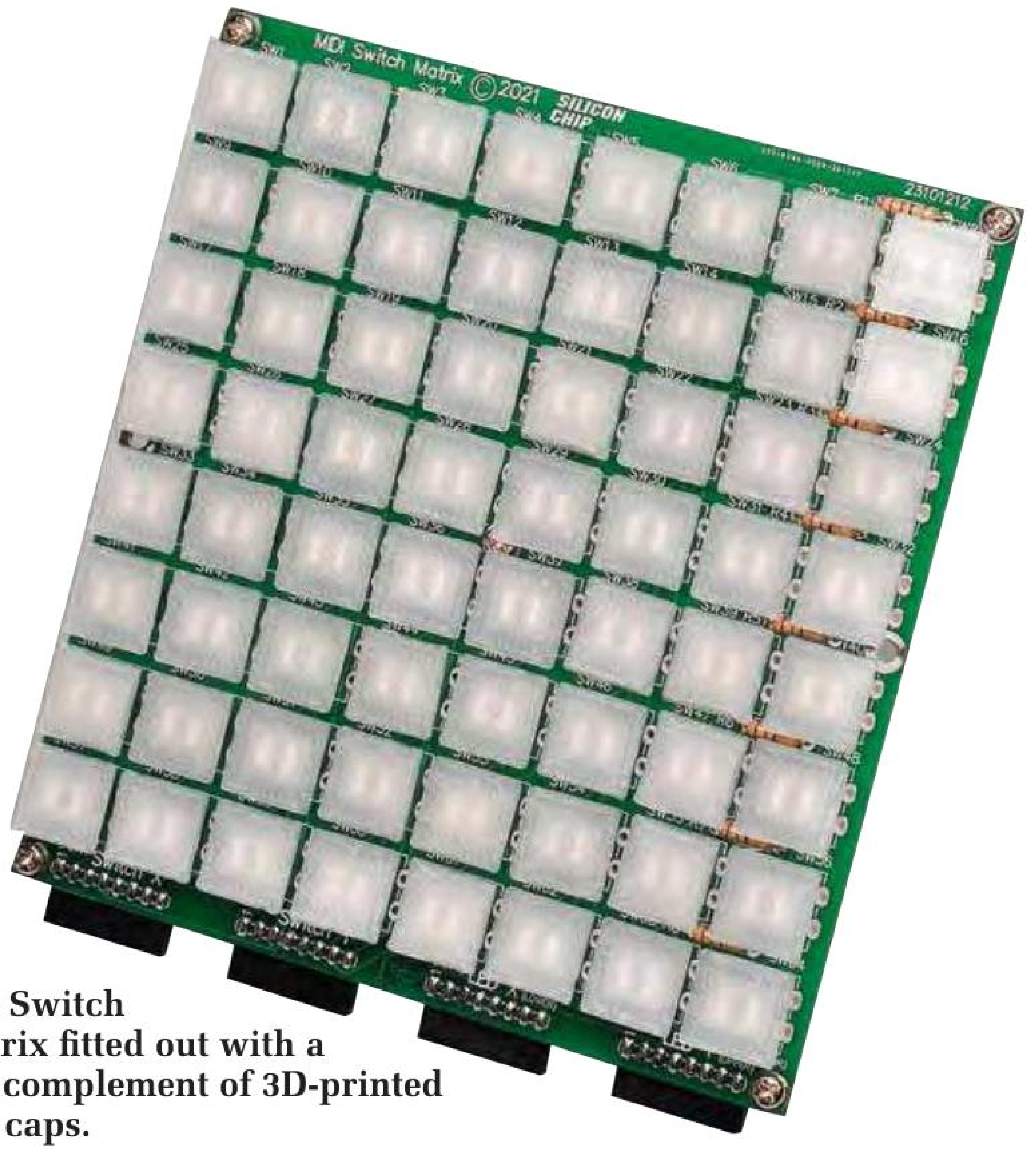
In line with our cheap-and-cheerful philosophy for this project, we have a simpler solution.

Fig.5 shows the minimal wiring needed, with the *MIDI Encoder Shield* at left and the LED Driver board (using the same PCB) on the right.

Our photos show this minimal arrangement too. We have soldered a 2-way female header to each PCB at the 5V/GND connections, and these are connected by a pair of jumper wires (red and blue).

The LED Driver PCB is simply our shield PCB from part one fitted with headers to break out the connections. There are also headers underneath to connect to the Leonardo.

The easiest way to solder these is to insert the headers into the Leonardo's sockets, slot the PCB onto the headers and then solder them. The pins are thus square and aligned.



The Switch Matrix fitted out with a full complement of 3D-printed key caps.

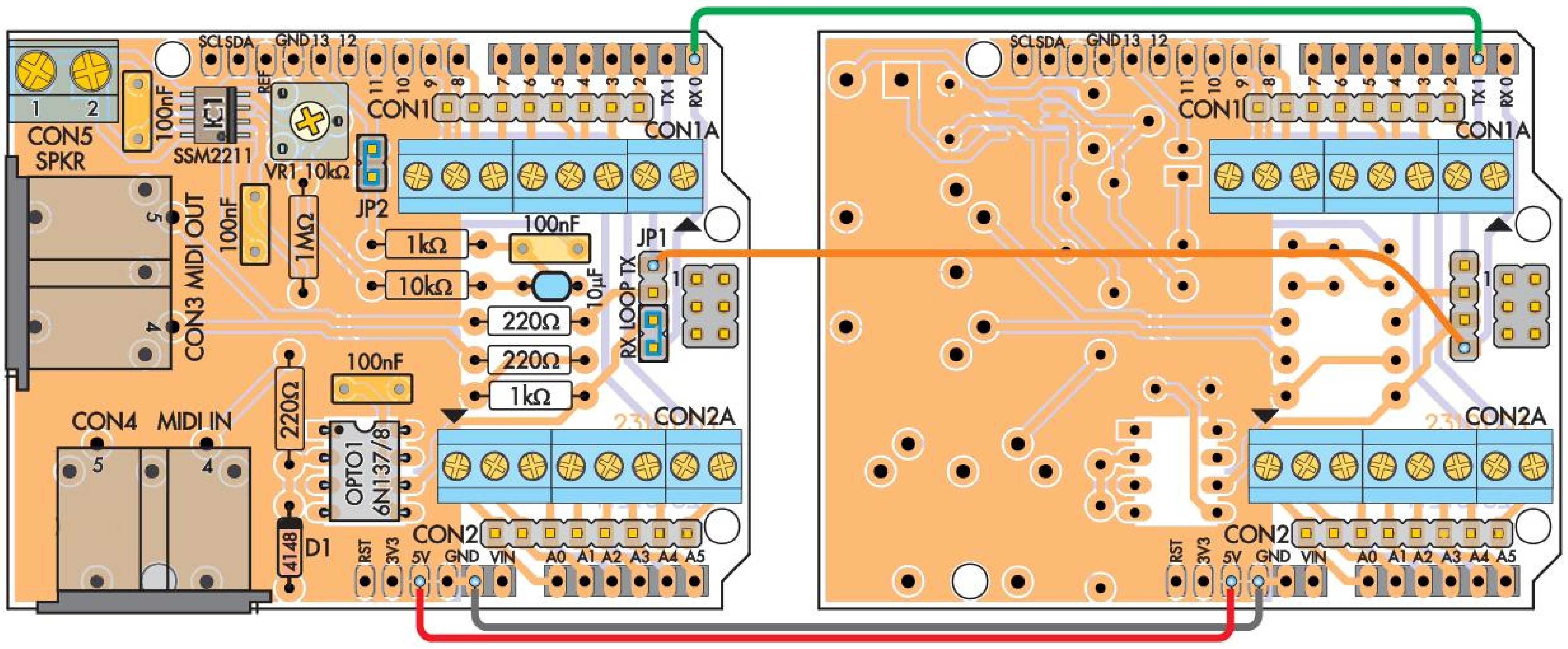


Fig.5: this wiring bypasses the MIDI connectors and allows the MIDI Encoder to both power and communicate directly with the LED Driver. Naturally, there is no isolation in this case! Although two wires are shown for data (green and orange), only one is needed as the pins at each end are connected by PCB traces.

We used socket headers for CON1 and CON2 to allow simple plug-plug jumper wires to be used, although these could even be soldered in place. Make sure to wire pin 1 of CON2 (*Shield*) to pin 1 of CON3 (*Matrix*) and pin 1 of CON1 (*Shield*) to pin1 of CON4 (*Matrix*).

The data line is connected at the *MIDI Encoder* end by piggy-backing it onto the TX jumper at JP1, while the LED Driver is connected to the RX header at JP1.

Parts list – additional parts for LED Driver

- 1 double-sided PCB coded 23101211, 69 x 54mm from the PE PCB Service
- 1 Arduino Leonardo module
- 1 10-way pin header *(shield headers to Leonardo)*
- 1 8-way pin header *(shield headers to Leonardo)*
- 2 6-way pin headers *(shield headers to Leonardo)*
- 2 8-way pin headers or sockets *(to connect to Matrix PCB)*
- 2 8-way jumper wires *(to connect to Matrix PCB)*
- 3 jumper wires *(to connect to MIDI Encoder)*

If you have a bare Leonardo at either end, you could wire from the TX pin (pin 1) of the MIDI Encoder Leonardo to the RX pin (pin 0) of the LED Driver Leonardo.

Don't forget that you will need the *Switch Matrix* variant with illuminated switches fitted; they should have their anodes oriented towards the top of the PCB.

Software

We've updated the MIDI Encoder software also to output the SYSEX LED data, so upload the **MIDI_ENCODER_LED_SERIAL_OUT** to the Leonardo which is acting as the *MIDI Encoder*.

The LED Driver Leonardo should similarly be programmed with the **MATRIX_LED_DRIVER_SERIAL** sketch.

Once that is done, and both boards are powered up, pressing any key should cause the corresponding LED to light up. If they don't match up, try swapping or rotating the connections to CON3 or CON4 of the *Switch Matrix*.

If you wanted to do something fancy, like have the LEDs 'radiate out' from each key pressed, you just need to make modifications to the **MATRIX_LED_DRIVER_SERIAL** sketch.

3D printed keycaps

The 16mm spacing on the *Switch Matrix* is a good compromise between compactness and usability. If the keys were much closer, there'd be a higher chance of pressing more than one key, while a wider spacing would quickly cause the PCB to blow up in size.

We made the off-hand comment last issue that 3D-printed keycaps would be an economical way to add finishing touches to an illuminated matrix. While 12mm tactile switches can be found with large buttons which are easy on the fingers, there are fewer options for the smaller illuminated parts.

Unfortunately, many small, illuminated switches only support small keycaps (around 10mm), which would look very odd on the 16mm spacing we have used. So we designed a 3D-printed keycap to suit the ILS series switches that we used.

We printed some of these in a translucent PLA filament (Jaycar's Cat TL4274), and it helped diffuse the light from the LEDs, although as they are so small, they were a fussy fit.

We've made the 3D files available for download if you want to 3D print your own keycaps and try them for yourself.

MIDI glossary

Channel: Each MIDI message can specify one of 16 channels, allowing data to be routed to or from different instruments while maintaining its source or identifying that it should be played back on a particular instrument. Our software uses a single, fixed channel which can be changed in the code.

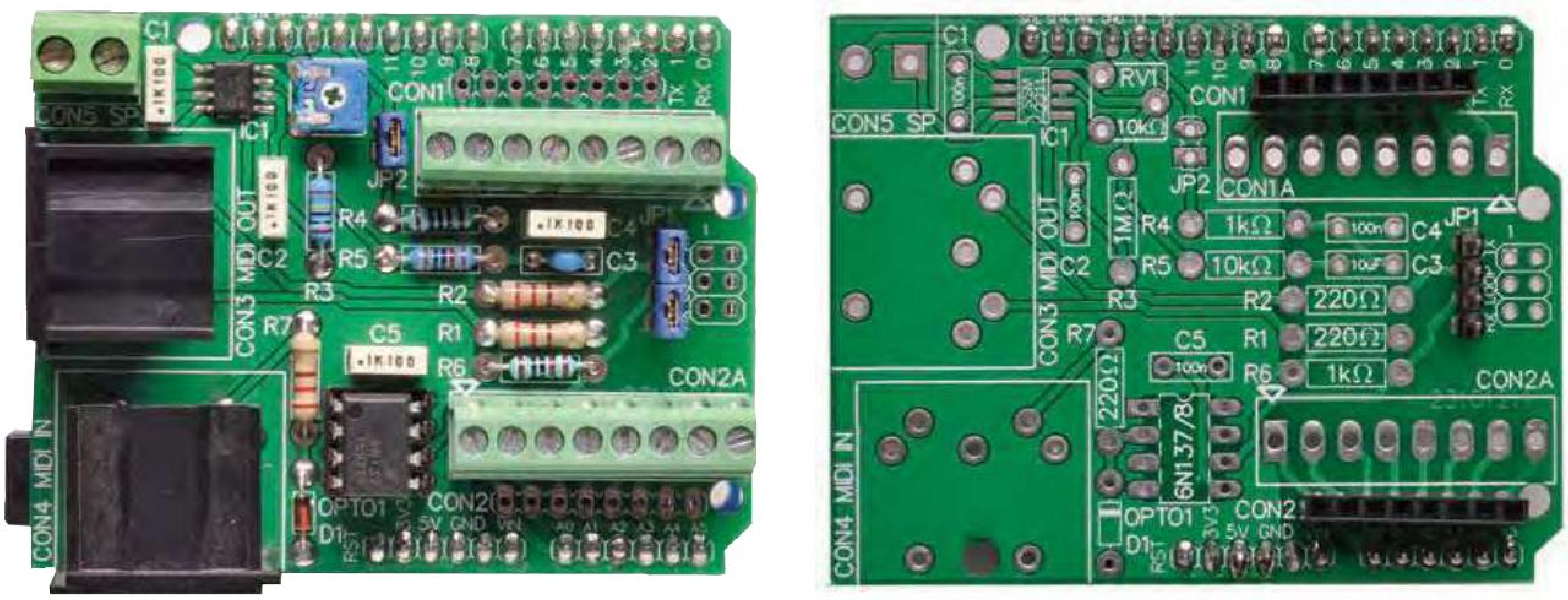
Message: The smallest unit of MIDI data is a message and corresponds to a single event (like a piano key being pressed or released) or a setting that is to be changed.

Note number: Each musical note is associated with a number in the range 0-127. Middle C is assigned to number 60. Our design implements 64 of these (in an 8x8 matrix), with the range start and end defined in the code.

Note-on and Note-off messages: The Note-on and Note-off messages correspond to events that occur during music playback and are the only messages that the Encoder generates. They include information about the channel, velocity (see below) and note number.

Status: The first byte of a message is called the 'status byte' and is marked as such by having its most significant bit set. Typically, the lower nybble (four bits) of the status byte contains a four-bit value indicating the channel number.

Velocity: Velocity is how fast the key on a musical instrument is pressed, but is usually manifested as how loud a note sounds (which is related to how fast, for example, a piano key is pressed). Our software uses velocity 64, which is the default for devices that can't detect key velocity. Like Note number, it can have the value 0-127, with 0 also corresponding to Note-off for some devices.

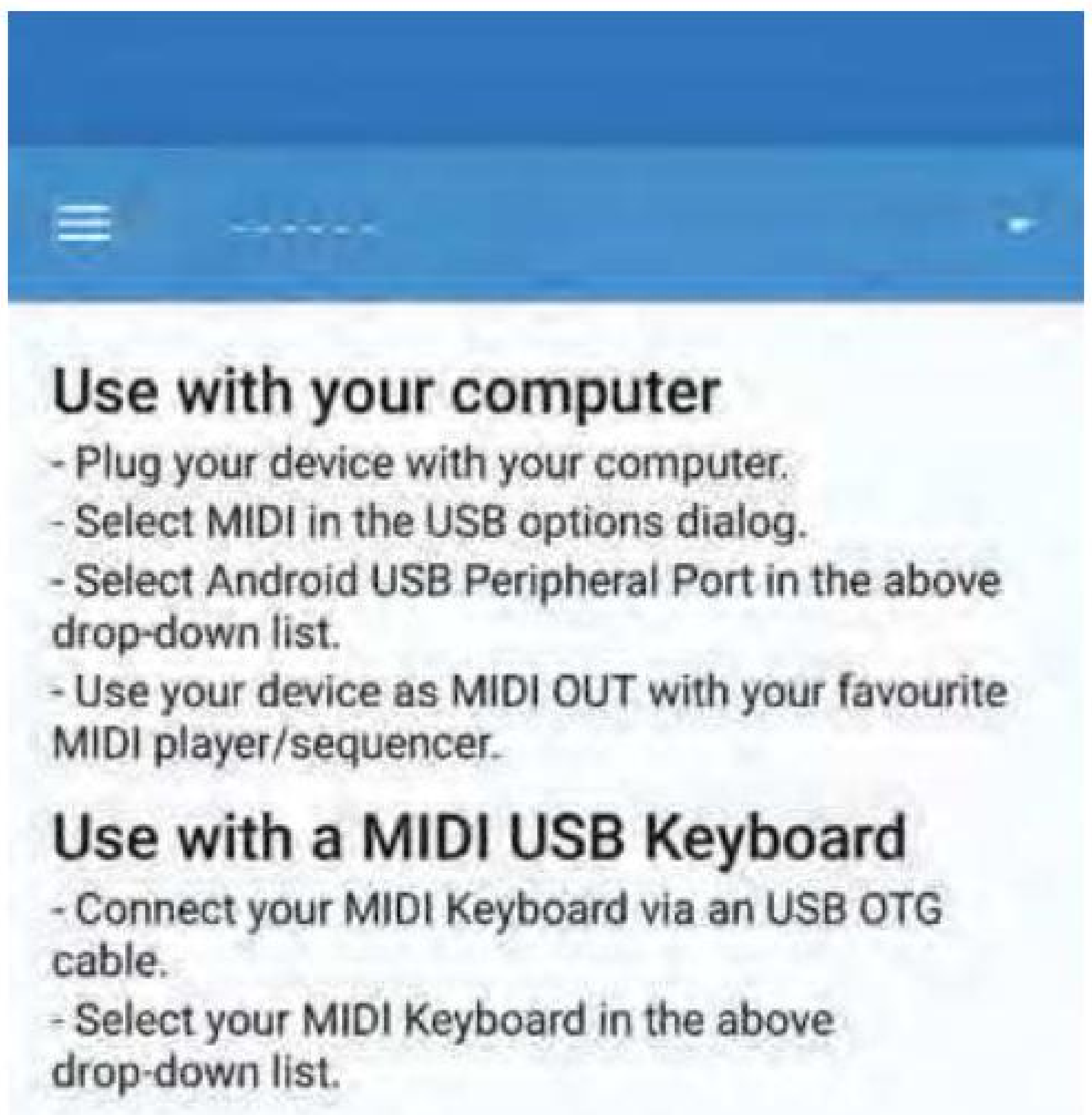


Here's the front and rear PCB photographs which match the overlay diagrams at left. Obviously, there's not much on the rear side of the PCB except sockets, as shown. These plug directly into the 'sandwiched' Leonardo board.

The accompanying photos show what the result looks like.

MIDI on Android

While testing our different MIDI hardware variants, including the *MIDI Encoder* PCB and the *Switch Matrix* PCB, we wondered if there was a way to connect the *MIDI Encoder* to a smartphone. With many people possibly having an old mobile phone around that could be repurposed, such an arrangement would be a quick, cheap and easy way to create a useful musical instrument.



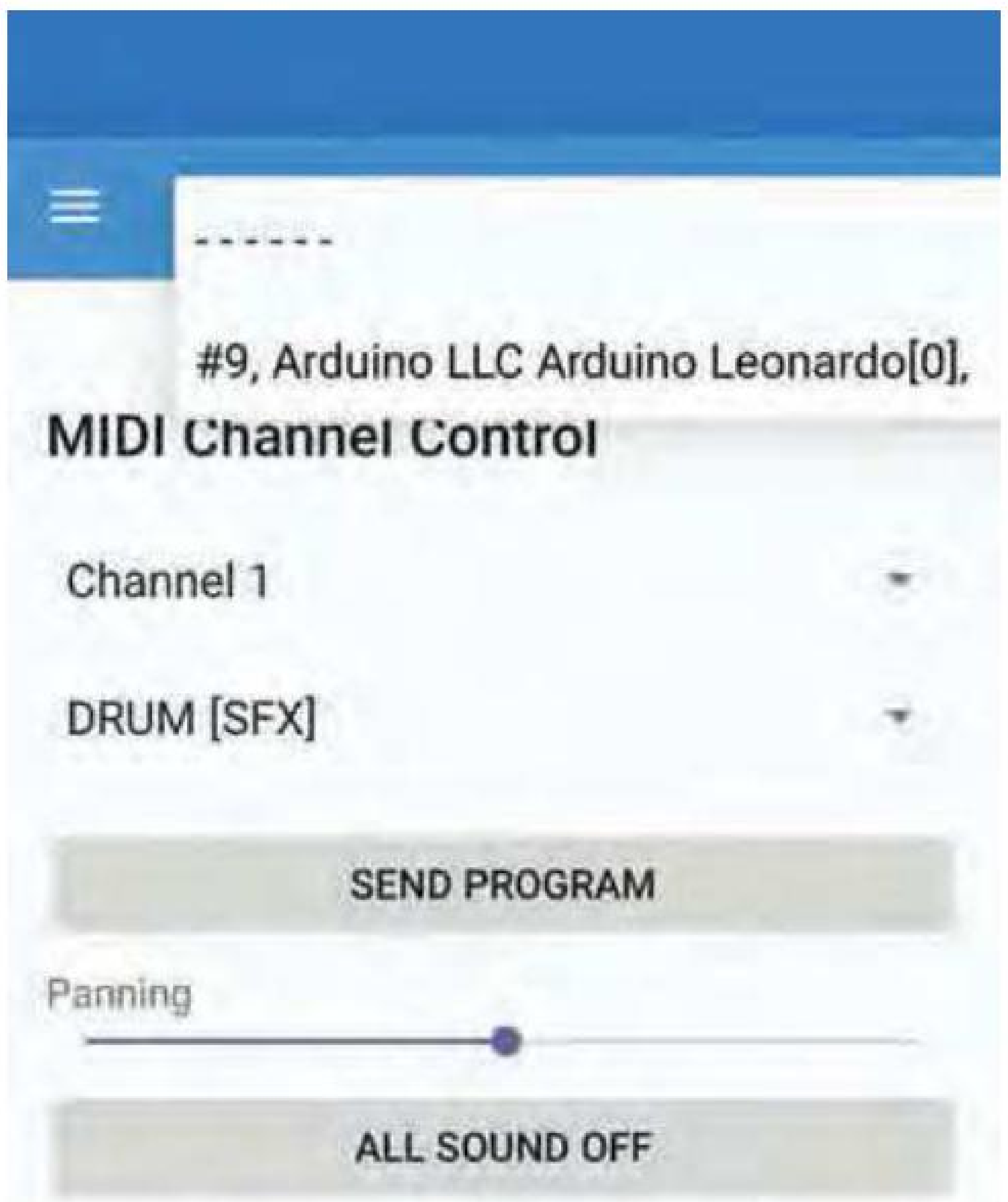
Use with your computer

- Plug your device with your computer.
- Select MIDI in the USB options dialog.
- Select Android USB Peripheral Port in the above drop-down list.
- Use your device as MIDI OUT with your favourite MIDI player/sequencer.

Use with a MIDI USB Keyboard

- Connect your MIDI Keyboard via an USB OTG cable.
- Select your MIDI Keyboard in the above drop-down list.

Screen1: the FluidSynth MIDI Synthesiser App has few controls, but that is part of what makes it easy to use. Once the MIDI Encoder (or other MIDI device) is plugged in, it becomes available from the top of the screen.



#9, Arduino LLC Arduino Leonardo[0],

MIDI Channel Control

Channel 1

DRUM [SFX]

Screen2: the MIDI Encoder appears as an Arduino Leonardo device when selected. The number shown is different every time the Encoder is reconnected, but this doesn't seem to cause any problems.

We only looked at Android devices because that is what most of us use. Our minimal research suggests that this might be possible on Apple devices (such as iPhones), but it's not something we've delved into.

Note also that there are many different types of Android phones, and we can't claim that this will work with all of them.

If you can check that your phone supports USB OTG (on-the-go) and has a fairly recent Android version, then you have a decent chance of success.

Android is not restricted to mobile phones; some tablets run Android, plus some other devices (for example, smart TVs).

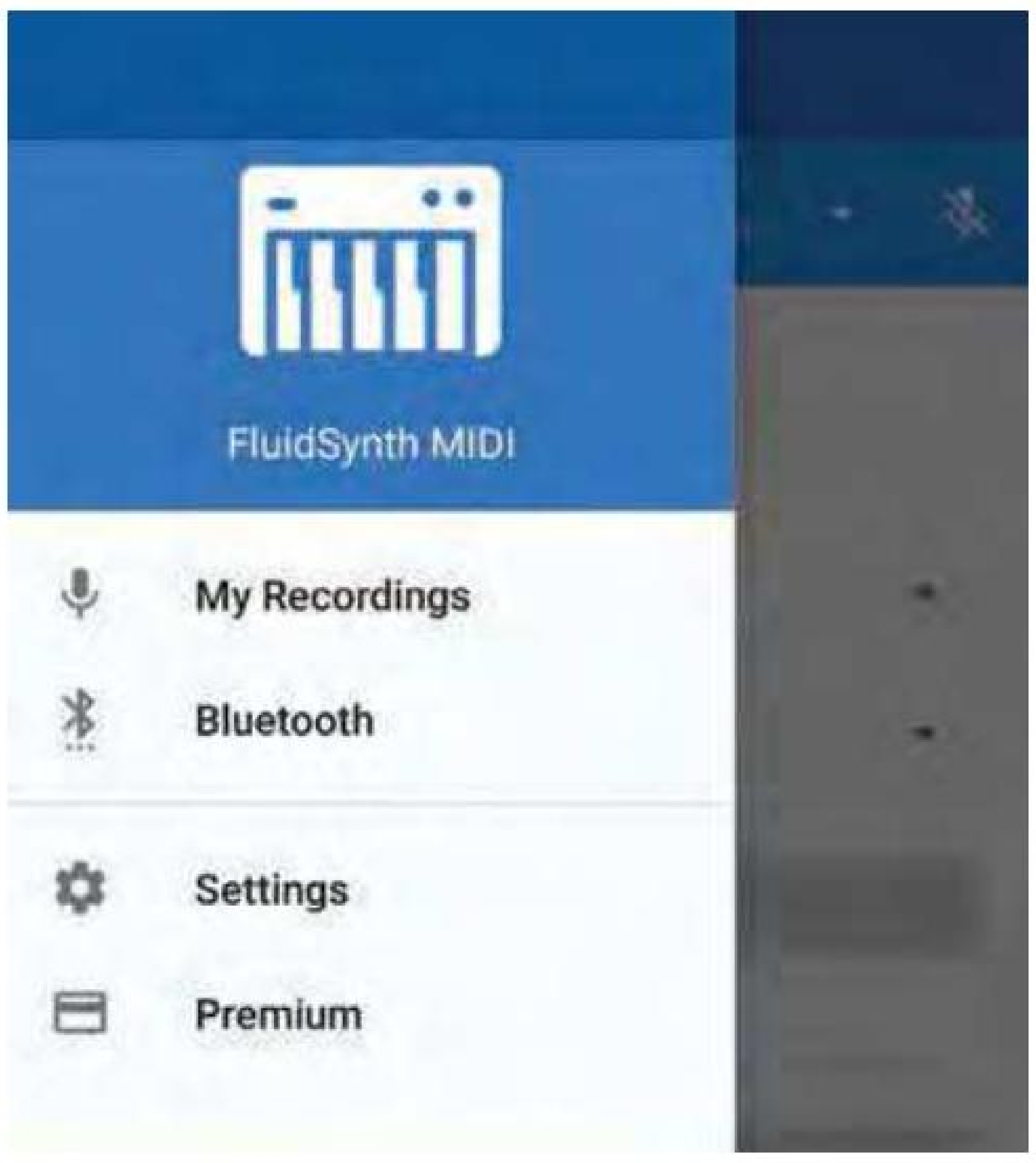
What you need

One thing that you'll almost certainly need is a USB on-the-go (OTG) adapter. This allows the USB socket on your phone to behave as a host device instead of a peripheral device. Not all phones support OTG, but it's quite common these days.

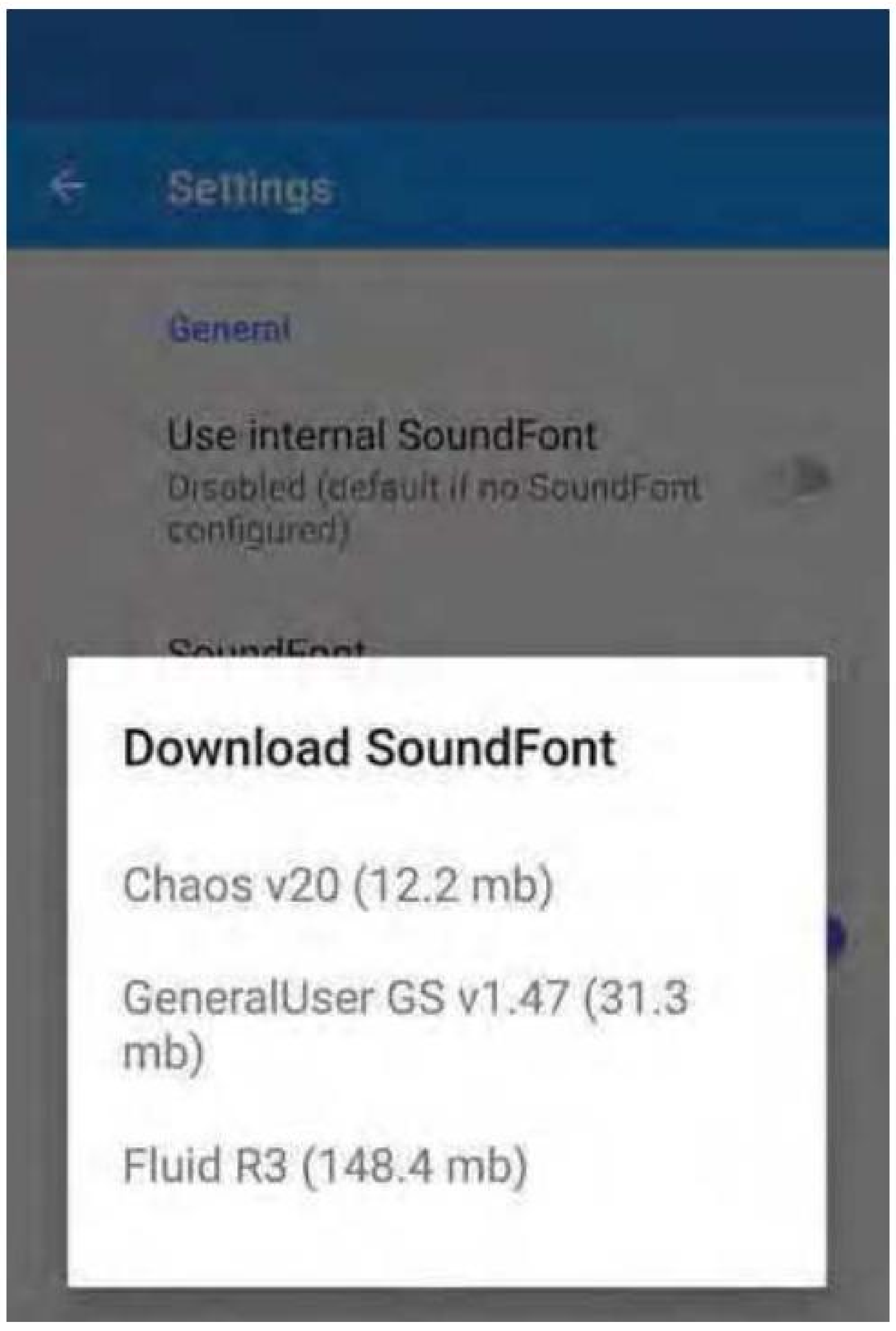
The OTG adapter will have a plug that suits the USB socket on your phone (micro-USB or USB-C) and a USB-A socket (such as you might find on a computer). For example, Jaycar Cat WC7725 (micro-USB lead) or Cat WC7709 (USB-C lead) should work. Or use Altronics Cat P1921 for micro-USB or Cat P1924 for USB-C.

Smaller adaptors are available which do not have any leads; they connect the devices directly. We like them because they're small enough to carry around in your pocket or bag. You can see one of these in our Android phone photo.

Indeed, an OTG adapter is a handy thing to have these days, with many phones having support for USB keyboards, mice and flash drives. We've even seen an app that lets you use one to program Arduino boards!



Screen3: we've only used the Settings option from the menu. Recordings are a paid premium feature that we did not test as we figured it would be easy enough to connect a 3.5mm stereo aux lead to the phone's jack to record audio.


Settings

General

Use internal SoundFont

Disabled (default if no SoundFont configured)

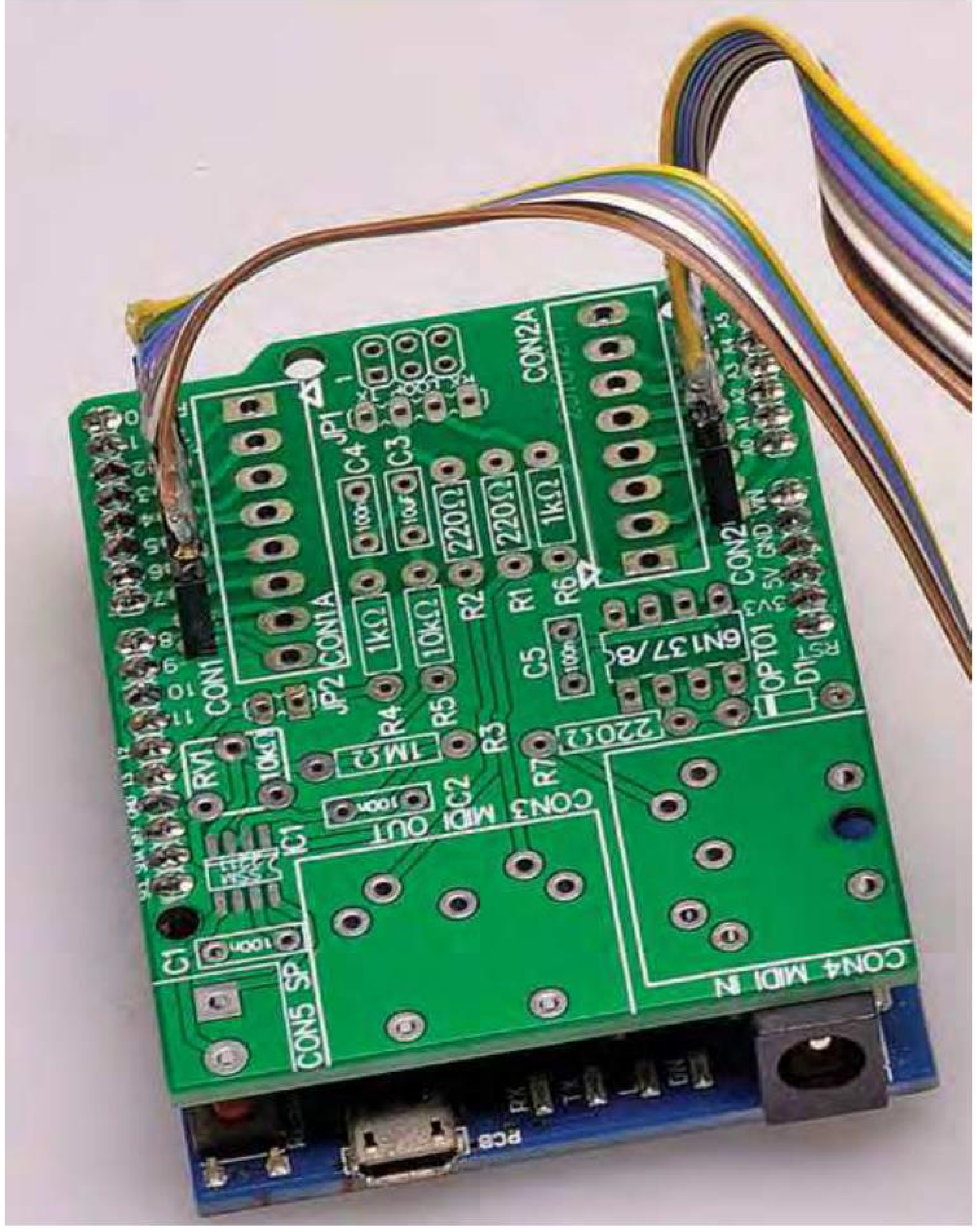
Download SoundFont

Chaos v20 (12.2 mb)

GeneralUser GS v1.47 (31.3 mb)

Fluid R3 (148.4 mb)

Screen4: it's only necessary to download the SoundFont file during initial setup. After this, you will just need to check that the MIDI Encoder is selected on the main screen before using it.



Our basic setup allows access to myriad options through musical instrument choices and SoundFont files. The Encoder PCB here is only fitted with headers to connect to the Switch Matrix.

Having said that, writing Arduino sketches on such a small screen isn't the easiest thing in the world.

Note that your phone and apps need to have support for the devices you want to attach. Fortunately, MIDI is supported as a Device Class Definition by the USB standard, meaning that any compliant USB MIDI device should work, without needing specialised drivers.

MIDI Apps

We don't have any affiliation to the following Android MIDI Apps; we found them by searching the Google Play Store.

The first one we tried was called MIDI Keyboard, which was able to recognise the attached Leonardo, but was limited to a single piano instrument. So we kept looking to see what other options were available.

The second App, called FluidSynth MIDI Synthesizer, gave a few more options. At the time of writing, it generally had positive reviews, and it also appeared to support downloadable SoundFont (.SF2) files. There is a paid upgrade available to allow recording on your device, but we were well entertained by simply playing sounds back through our phone speaker. A connection using a 3.5mm stereo aux cable should be sufficient to connect the audio to other equipment for amplification or recording.

A pair of 2-pin header sockets soldered back to back and with their pins bridged can be used as a jumper that provides extra sockets to tap into. We used this arrangement to break out the MIDI signal from the MIDI Encoder board from JP1, with an extra jumper wire leading to the LED Driver board.

Installing the App was quite simple. It works with Android 6 and later. We found that it needed permission to access device storage; this is required to access the downloaded SF2 files.

Screen1 shows its initial screen. When a MIDI device (like the *MIDI Encoder*) is plugged in via an OTG adapter, it appears in the dropdown menu at the top of the screen.

Screen2 is shown when such a device is selected, giving control over the MIDI device. From the menu icon at top left, select Settings (Screen3) and choose 'Download a SoundFont'. The Chaos V20 option (Screen4) is the smallest of the download options, and gave many different sounds.

Returning to the main screen (Screen2) then allows the various channels and instruments to be configured. Having done that, you can use the *MIDI Encoder* to play through the phone's speaker.

The Channel and Instrument dropdowns allow specific instruments to be allocated to different channels. Once each channel/instrument combination is set, press the 'SEND PROGRAM' button to activate it.

By default, the *MIDI Encoder* only delivers data on channel 1, but we have created a software variant that outputs on four channels instead.

The Arduino sketch is named **MIDI_ENCODER_4_CHANNEL**, and when uploaded to the *MIDI Encoder* and *Switch Matrix* hardware, will generate events on channel 1 when S1-S16 are pressed, channel 2 for S17-S32, channel 3 for S33-S48 and channel 4 for S49-S64.

You might find that this combination works very well for triggering sound effects. Look near the bottom of the instrument list, among the percussion instruments.

Conclusion

With the addition of a second Leonardo board and not much else, we can add controllable LEDs to our *MIDI Encoder* and *Matrix*. And since our system uses the existing MIDI hardware, our software could be modified to give MIDI control over other things too.

Using our *MIDI Encoder* and *Switch Matrix* with an old Android phone is a very economical way to access a full range of playable sounds.

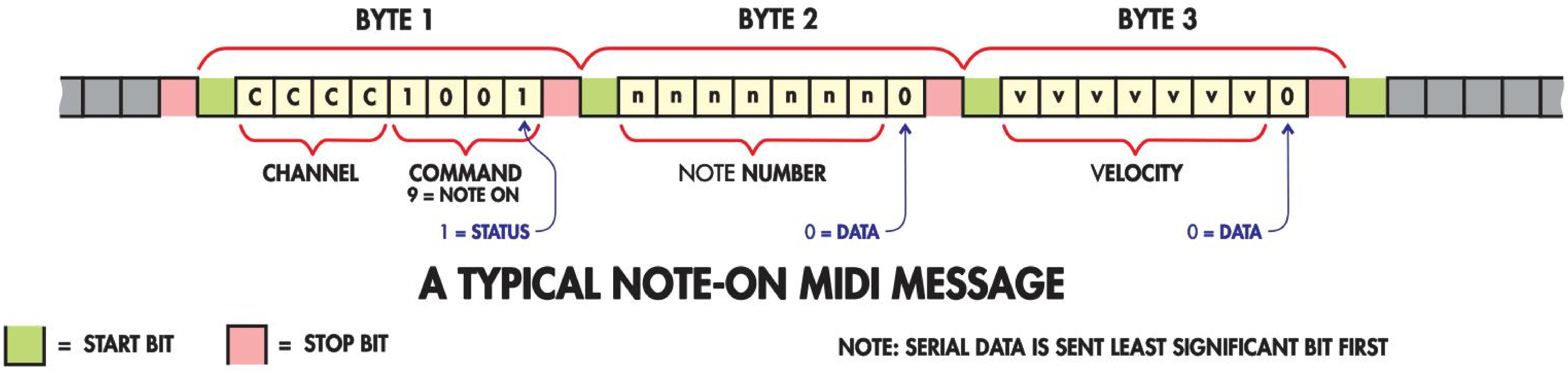


Fig.6: the arrangement of a typical 'Note-on' message. The first byte has its most-significant bit is set to flag that it is the start of the message. The high nybble of 9 means that this is a Note-on message (8 would mean Note-off), with the low nybble containing the channel number. The following bytes carry 7-bit values for note number and velocity.

WHAT IS MIDI?

MIDI stands for 'Musical Instrument Digital Interface'. It's a standardised system for communicating between electronic musical instruments, keyboards, controllers and sequencers (including PC-based sequencers). The original MIDI standard was agreed on by a group of musical instrument makers in 1983, and has been used and extended since then.

The last time we looked at MIDI was before the Arduino phenomenon had fully developed. Arduino has made it very easy to interface electronics to MIDI equipment. People have created an assortment of controllers, instruments and even synthesisers with a variety of sounds using Arduino.

A MIDI 2.0 standard was released in January 2020, and is intended to be backwards-compatible with the original MIDI specification. The new standard is not yet in widespread use and is still undergoing testing.

Electrical protocol

The standard specifies events that occur (such as the start or end of notes being played), which are encapsulated in messages that are transmitted between devices. The 'original' MIDI relies on serial data communication at 31.25kb/s using asynchronous 5mA current-loop signalling, with the current provided by the transmitting end.

This means that each byte of a MIDI message takes only 320µs to be transmitted (counting start and stop bits). Since MIDI messages are either one, two or three bytes in length, this means that over 1000 such messages can be sent each second via a single MIDI cable.

Each MIDI cable carries only one signal, so for bidirectional communication, two cables must be used. The cables themselves use shielded two-conductor wire.

All MIDI cables are fitted with standard 180° 5-pin DIN plugs at both ends. However, only pins 4 and 5 are used for the actual current loop signalling (wired 4-4 and 5-5). Pins 1 and 3 are left unconnected, while the shield braid is connected to pin 2 at each plug.

Inside MIDI equipment, pin 2 is connected to earth only on MIDI OUT sockets. This provides shielding via earthed cable shield braids without creating earth loop problems.

Unlike most other current-loop signalling protocols, current only flows in a MIDI link when data is being transmitted. This allows MIDI cables to be 'hot' plugged and unplugged without any problems, as long as they are not in active use.

All MIDI inputs are provided with 3kV of galvanic and electrostatic isolation via an optocoupler to prevent equipment damage due to wiring errors or component faults. For proper MIDI communication between equipment, a MIDI OUT or MIDI THRU socket at one end must be connected to a MIDI IN socket at the other.

That is what we call the 'hardware' MIDI implementation. There also exists a USB implementation that allows for much faster communication. This is not merely a USB-serial type of translation (although software exists to use USB-serial converters for this purpose).

Jaycar's Cat XC4934 USB MIDI Interface is one example of hardware for translating between these two protocols for device interconnection.

Since MIDI is not much more than a series of data bytes, various other 'hardware transports' have been used. These include FireWire, LAN and even wireless transmission methods.

Logical protocol

Each message starts with a byte that has its most significant bit set, and the remaining bytes (for practically all messages) has the most significant bit cleared. This means it is very easy to serialise and packetise the data for conversion over other transports.

There is a single main controller or sequencer in most MIDI systems from which most of the MIDI messages originate (often the computer, or perhaps a keyboard or digital audio workstation). When these messages must be sent to more than one instrument, they can be distributed in either 'star' or 'daisy-chain' manner, as desired.

It's possible to combine two MIDI streams. However, a device to do that is not trivial to implement, as it must handle the case when two messages arrive at the same time and queue them for consecutive output without delaying them excessively.

There's no need to worry much about the actual code messages sent over the MIDI links. Nowadays, that is handled by a sequencer or other software running in the PC and by firmware running in the other instruments and keyboards.

It's probably enough to know that most MIDI messages are short commands to allocate a particular instrument to a specific channel, to tell it to start or stop playing a particular note, to change the instrument's attack/decay or other performance parameters, and so on.

As mentioned earlier, these commands are generally in the form of three-byte messages (see Fig.6). However, some configuration and/or system management messages are only one or two bytes long. Longer, equipment-specific configuration messages also exist, for example, to load digital audio samples into a sampler.

File format

Using a PC-based music editing and sequencer program, and perhaps with a MIDI music keyboard to feed in the actual notes, you can assemble a complete sequence of MIDI commands to play a piece of music – eg, on the 'instruments' in a synthesiser.

The synthesiser can then be made to 'perform' that piece of music by merely sending the sequence to it, via the MIDI link. When you're happy with the result, you can save the sequence on disk as a MIDI music file. These have a standardised format and are identified with a '.MID' extension.

The .MID file format is essentially a series of MIDI messages after a header, stored in chunks (in a similar fashion to .WAV file chunks) and intermingled with timing data to ensure that the messages can be played back correctly.

It's important to realise that although a MIDI music file may look superficially similar to a .WAV file of a digital sound recording, it's really quite different. It's more like an electronic equivalent of sheet music – simply a sequence of detailed instructions describing how to play the music.

In this case, they are instructions for electronic instruments rather than for human players. And depending on the instrument that is providing playback, the sound that is output can vary substantially.

Software

The advent of Arduino-compatible boards with an integrated USB peripheral such as the Leonardo (based on the ATmega32u4 microcontroller) makes it easy to implement a USB MIDI interface. And there is much PC software around that can work with USB MIDI devices.

While we were testing our design, we experimented with MuseScore (**https://musescore.org/en**), an open-source score-writing program and Anvil Studio (**www.anvilstudio.com**), a digital audio workstation program. Both can act as a synthesiser, producing sounds based on incoming MIDI messages.

If you would like to delve further into the technicalities of MIDI, then take a look at the MIDI Manufacturers Association website here: **www.midi.org/specifications**

Of course, you're not limited to using our *MIDI Encoder* with this App. You might want to modify the Arduino sketch to provide your own interface, or even plug in another USB MIDI device.

Links

SoundFont files
https://bit.ly/pe-may22-sfz

FluidSynth MIDI Synthesizer App
https://bit.ly/pe-may22-fsms

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Digital FX Unit

IN
9-12
Effects mix
Output level
input
Min
Max
C
B
A
effects parameters
SILICON CHIP Digital FX
BYPASS
PATCH
2
3
4
5
6
7
9
10
11
12
13
14
15
16

Our new *Digial FX Unit*, introduced last month, can produce 15 different effects for musicians or recording technicians to customise their instruments and sounds. You can customise eight of those effects – and this article describes how to create and install different effects patches into the unit's EEPROM.

Part two – by John Clarke

While we have included a great variety of pre-programmed effects in the EEPROM supplied for our new *Digital FX Unit* (adding to those already present within the SPIN FV-1 chip), you might want to change some of these effects patches. That will ensure that the *Digital FX Unit* has the effects you want.

Numerous effects patches can be freely downloaded. If you are an avid programmer, free software is available with graphical programming to write your own effects patches – more on that later.

To program the *Digital FX Unit's* EEPROM, you need an EEPROM programmer suitable for the 24LC32A. We will describe how you can do this with a Microchip PICkit 2 or PICkit 3 programmer. (Do see the box on page 25.)

Available effects patches

First though, let's look at the pre-made effects that are freely available. There is a reasonably comprehensive list at: **https://mstratman.github.io/fv1-programs/**

In that set of listings, you can see details for each by selecting the 'MORE' box. This additional information often includes details on the functions of VR7 (A control), VR6 (B control) and VR5 (C control) on the *Digital FX Unit*. These are labelled as 1, 2 and 3 in the program listings.

The assembler program for the selected effects patch can be downloaded from the site by choosing the cyan 'Download SpinAsm' link at the bottom of the effect patch detail area (see Screen1 opposite).

If you want to access more programs, these are available directly from the SPIN semiconductor website at: **www.spinsemi.com/programs.php**

You can download these files to any folder you like, as long as you remember where you put them.

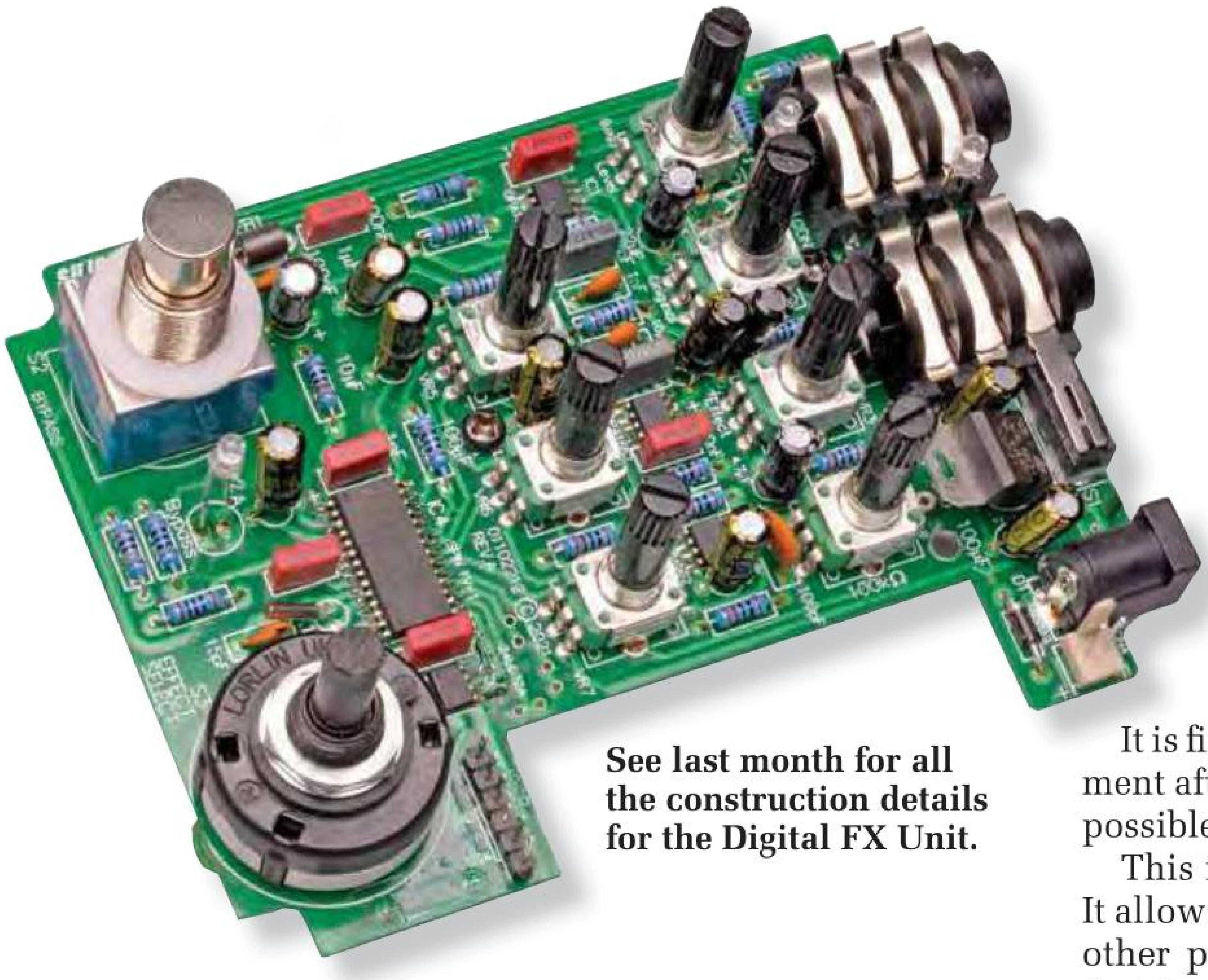
Collation

Once you have all your selected effects patches, these will need to be collated in a form suitable for programming into the EEPROM. Each effects patch is placed into a separate 512 x 8-bit memory block, and there are eight such memory blocks in the 32kbit EEPROM. To generate the required data, you will need to use the Spin Semiconductor assembler called 'SpinAsm' (note: Windows only).

SpinAsm can be downloaded from the Spin Semiconductor website linked above; it is called 'SpinAsm assembler for the SPN1001 V1.1.31 (Windows executable)'.

Patch	Effect	Adjustment C	Adjustment B	Adjustment A
1	**Chorus-reverb**	Chorus mix	Chorus rate	Reverb mix
2	**Flange-reverb**	Flange mix	Flange rate	Reverb mix
3	**Tremolo-reverb**	Tremolo mix	Tremolo rate	Reverb mix
4	**Pitch shift**	-	-	±4 semitones
5	**Pitch echo**	Echo mix	Echo delay	Pitch shift
6	**Test**	-	-	-
7	**Reverb 1**	Low filter	High filter	Reverb time
8	**Reverb 2**	Low filter	High filter	Reverb time
9	**Octaver**	Down octave level	Up octave level	Dry mix
10	**Pitch shift glider**	Glide	Depth	Rate
11	**Oil can delay**	Feedback	Chorus width	Time rate
12	**Soft clip overdrive**	Tone	Volume	Gain threshold
13	**Bass distortion**	Dry/wet mix	Tone	Gain
14	**Aliaser**	-	-	Sampling rate
15	**Wah**	Filter Q	Sensitivity	Reverb
16	**Faux phase shifter**	Feedback level	Time	Speed width

Table 1: preprogrammed effects patches *(9-16 can be changed)*



See last month for all the construction details for the Digital FX Unit.

If you need more information regarding installing this program, see the installation guide later in this article.

Once you have installed SpinAsm, move the saved effects patch files (.spn extension) to the folder: **C:\Program Files (x86)\SpinAsm IDE\spinsrc**

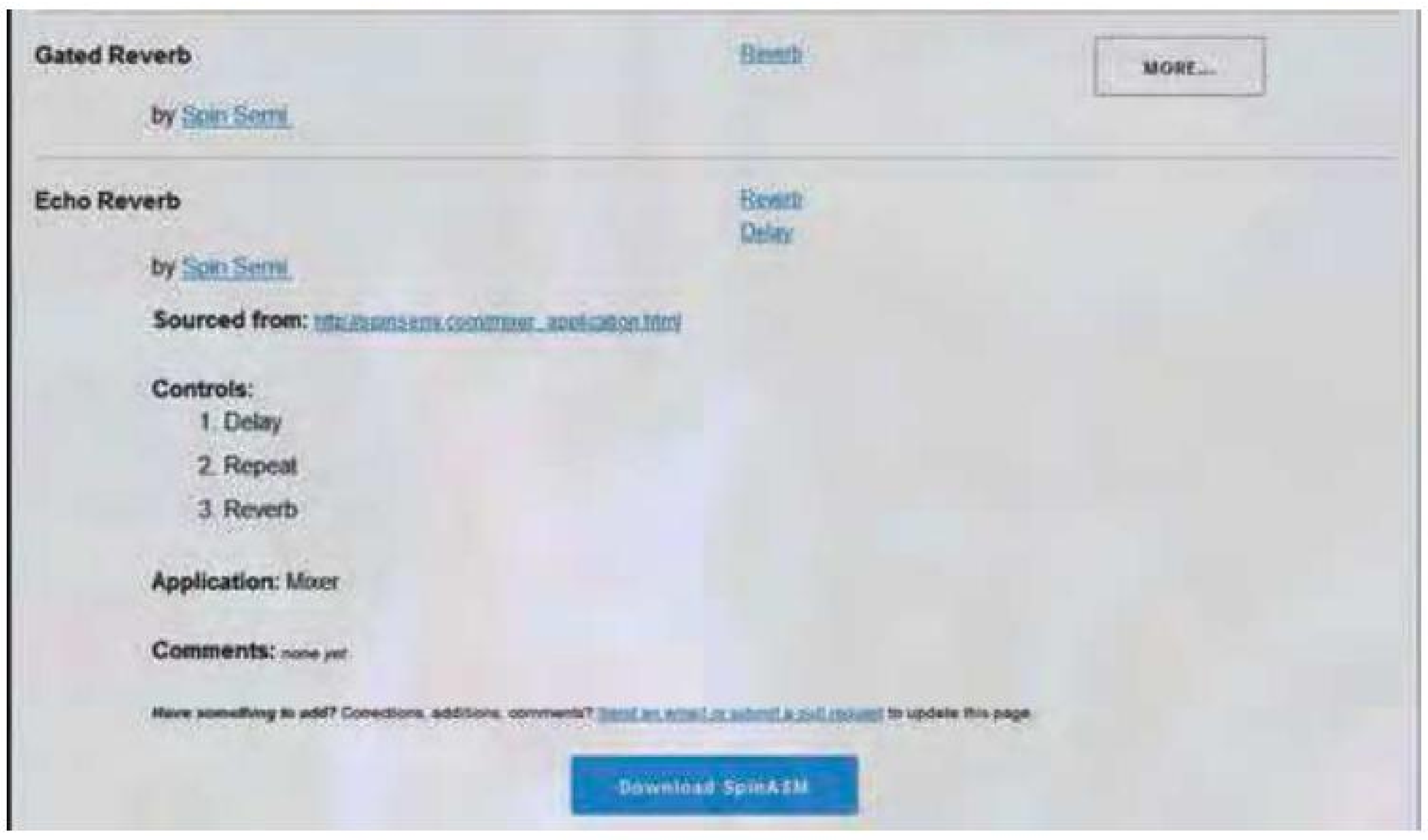
To open the SpinAsm program, right-click on the SpinAsm icon and select 'Run as Administrator'. (If you do not run as Administrator, your work will be not be saved.)

You will be asked whether you want this app to make changes to your computer. After clicking 'Yes', the program opens. Left-click on the 'Open Project Dialog' icon just to the right of the Spin icon (see Screen2).

This opens up a table of PROG0 to PROG7, where you can place the required effects patches, as shown in Screen3. To select the first effects patch, right-click on the PROG0 box in the (UNCHANGED-NO OVERWRITE) area and select Load File Entry from the project dialog box (Screen4). Then, select the required file from the folder: **C:\Program Files (x86)\SpinAsm IDE\spinsrc\**

Note that you can change the directories for file locations by selecting the tree icon just to the right of the project dialog icon (Screen5). However, we will describe the setup using the default directory locations, as shown.

With the first patch selected (Screen6), use the same technique to load the patches for PROG1 to 7. You do not need to load all PROG locations if you don't need all eight effects used. However, do note that the programs you wish to load must start at PROG0 and continue with successive PROG locations.



Gated Reverb

by Spin Semi

Echo Reverb

by Spin Semi

Sourced from: http://spinsemi.com/mixer_application.html

Controls:

1. Delay
2. Repeat
3. Reverb

Application: Mixer

Comments: none yet

Have something to add? Corrections, additions, comments? Send an email or submit a pull request to update this page.

Screen1: you can download a range of pre-made effects patches from the Spin Semi website as 'SpinASM' files. These can then be compiled and uploaded to the EEPROM on the Digital FX Pedal.

Table 2. ICSP header pin mapping.

ICSP header pin	24LC EEPROM pin	Function
1	-	$\overline{\text{MCLR}}$ / V_{pp}
2	8	V_{dd} (positive supply)
3	4	GND / V_{SS} (0V)
4	-	PGD (Data)
5	6	PGC/SCL (Clock)
6	5	SDA (Data)

Table 2: ICSP header pin mapping

It is fine to have the UNCHANGED-NO OVERWRITE comment after the last program entry if you do not fill up all the possible programs.

This is meant for use with the SPIN development board. It allows single-location programming without affecting the other programmed locations in EEPROM. We don't use that feature, however.

Once all the required programs are loaded, select the Save button and save the project under a suitable name. We named ours **SC Patches.spj** – see Screen7.

Once saved, select the 'Intel Hex' checkbox in the lower-left portion of the project dialog box and press the 'Build' button. The HEX file will then be saved to the following folder: **C:\Program Files (x86)\SpinAsm IDE\hexout**. It will be named the same as the project saved, but with a .hex extension.

In our example, it is **SC Patches.hex** – this is the file you need to program into the EEPROM. If the hex file and project file were not saved, that probably means that SpinAsm was not run as an Administrator.

Programming the EEPROM

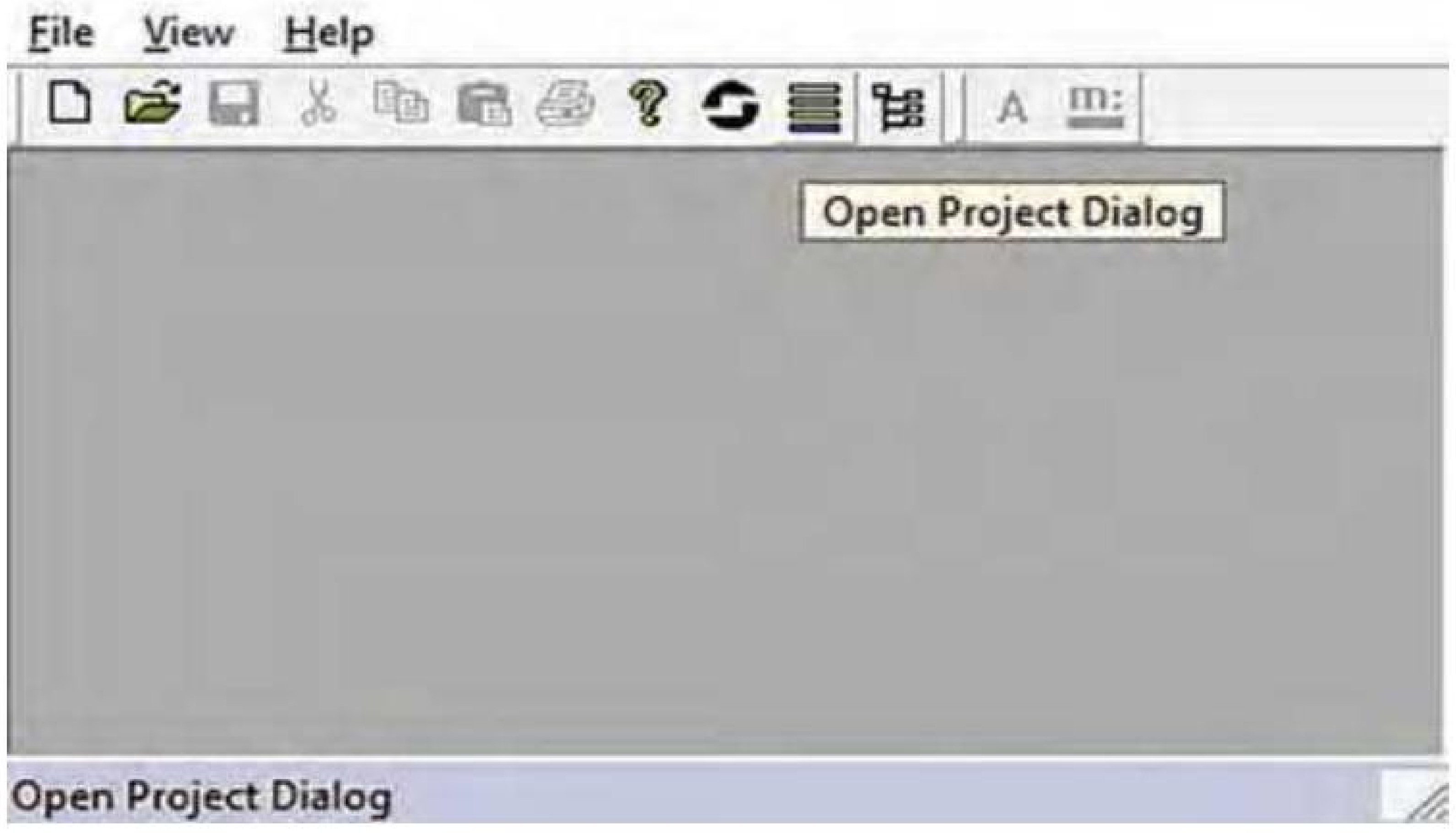
There are several ways to program the EEPROM. If you have an EEPROM programmer suitable for the 24LC32A, that would be the easiest way to do it.

If you have a Microchip PICkit 2 or PICkit 3, you can program the EEPROM using free software that you can download from Microchip's website. We are not using MPLAB X IPE, as we would for PICs, as it does not support this EEPROM.

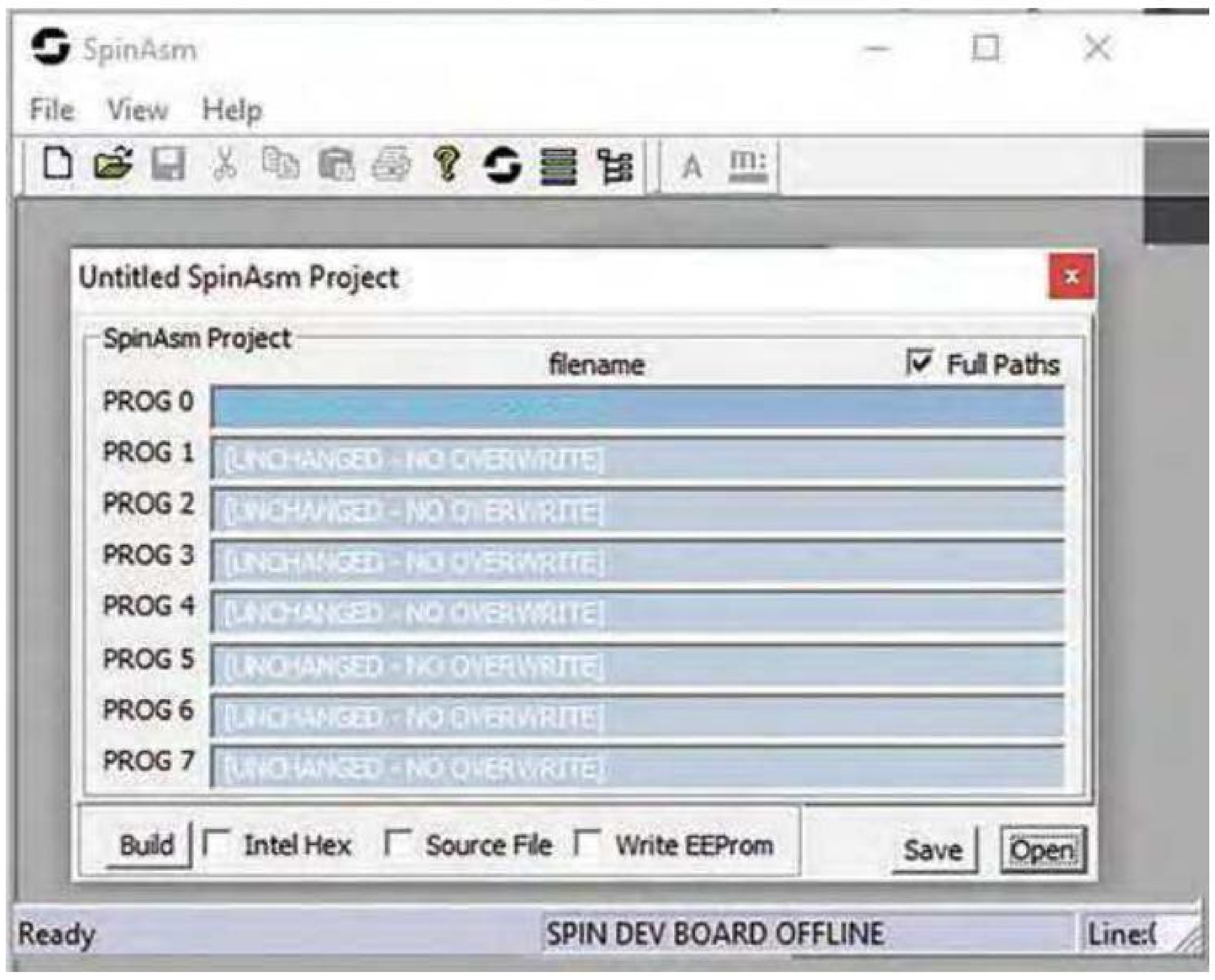
For PICkit 2, download the software. **PICkit 2 Firmware V2.32** and user's guide *PICkit 2 Microcontroller Programmer User's Guide*. Both can be found at: **https://bit.ly/pe-may22-pk2**

This is very similar to the PICkit 3 programming software that we now describe.

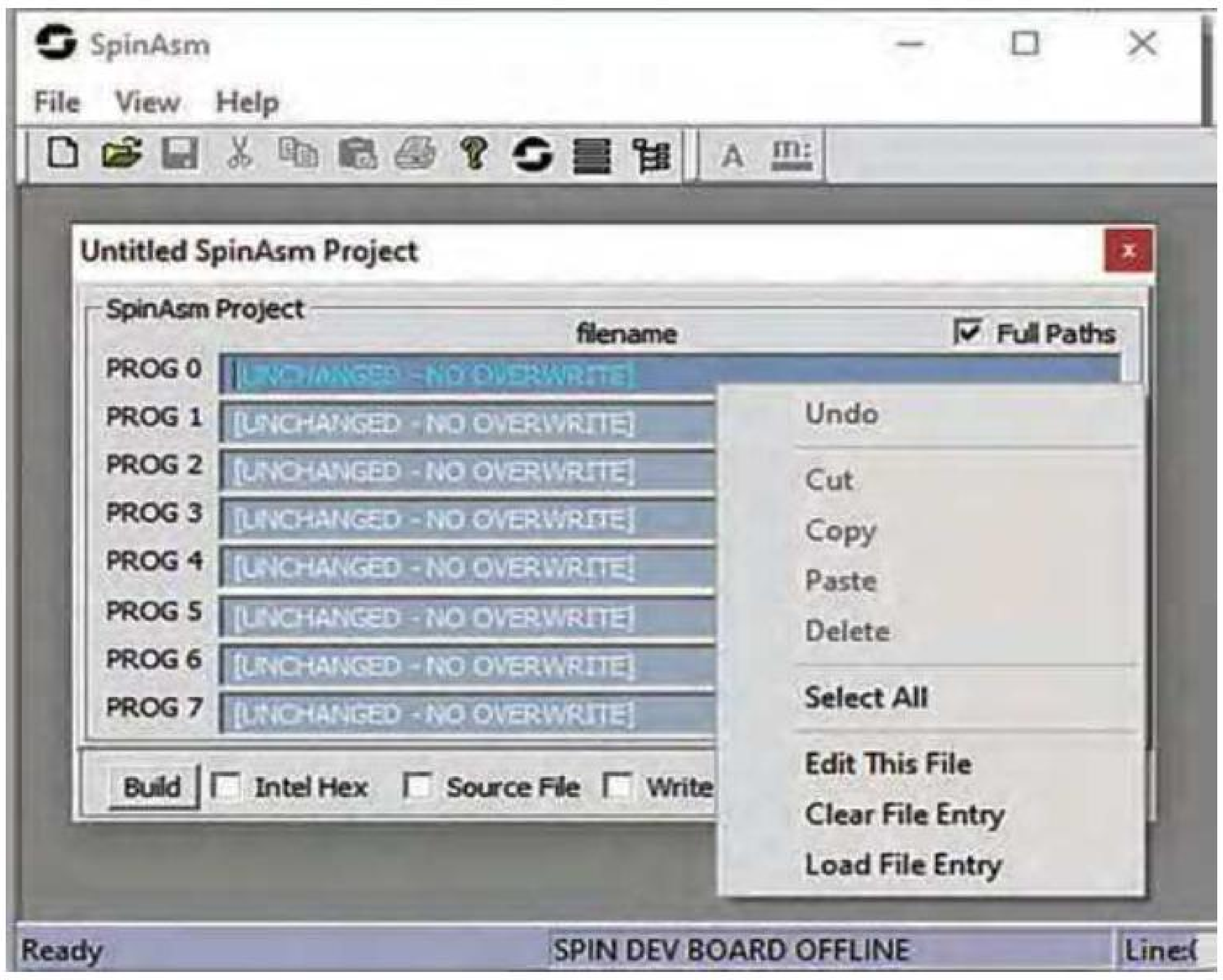
The PICkit 3 is the successor to the PICkit 2, and while PICkit 2 is suitable for directly programming the 24LC32A EEPROM, the PICkit 3 requires some modifications. It also



Screen2: use the Open Project Dialog button in SpinASM to load one of the effects patch ASM files you have downloaded.


SpinAsm
File View Help
Untitled SpinAsm Project
SpinAsm Project
filename
☑ Full Paths
PROG 0
PROG 1 [UNCHANGED - NO OVERWRITE]
PROG 2 [UNCHANGED - NO OVERWRITE]
PROG 3 [UNCHANGED - NO OVERWRITE]
PROG 4 [UNCHANGED - NO OVERWRITE]
PROG 5 [UNCHANGED - NO OVERWRITE]
PROG 6 [UNCHANGED - NO OVERWRITE]
PROG 7 [UNCHANGED - NO OVERWRITE]
Build ☐ Intel Hex ☐ Source File ☐ Write EEProm
Save Open
Ready
SPIN DEV BOARD OFFLINE
Line:(

Screen3: when loading a SpinASM file, you will be prompted to select which of the eight available EEPROM slots it should go into. See our comments in the text about large (512-byte) patches needing to go into the last slot (PROG 7).


SpinAsm
File View Help
Untitled SpinAsm Project
SpinAsm Project
filename
☑ Full Paths
PROG 0 [UNCHANGED - NO OVERWRITE]
PROG 1 [UNCHANGED - NO OVERWRITE]
PROG 2 [UNCHANGED - NO OVERWRITE]
PROG 3 [UNCHANGED - NO OVERWRITE]
PROG 4 [UNCHANGED - NO OVERWRITE]
PROG 5 [UNCHANGED - NO OVERWRITE]
PROG 6 [UNCHANGED - NO OVERWRITE]
PROG 7 [UNCHANGED - NO OVERWRITE]
Undo
Cut
Copy
Paste
Delete
Select All
Edit This File
Clear File Entry
Load File Entry
Build ☐ Intel Hex ☐ Source File ☐ Write
Ready
SPIN DEV BOARD OFFLINE
Line:(

Screen4: after right-clicking on one of the slots, you are presented with a menu. Select the 'Load File Entry' option, and you will be prompted to choose a file to load into that slot.

needs to be loaded with a PICkit 2 emulator to work.

In this article, we describe how to program the EEPROM using the Microchip PICkit 3 programmer, as that is the one we think readers are most likely to have. We tested one clone version of PICkit 3, and found it would not connect correctly. Different clone versions might work, but we cannot recommend using anything but the genuine Microchip PICkit 3.

The *Digital FX Unit* includes an in-circuit serial programming connection (ICSP) suitable for programming the EEPROM. The PICkit 2 or PICkit 3 plugs directly onto the ICSP header. However, you might need to use jumper wires to make suitable connections to the ICSP header for other programmers.

Table 2 shows the connections from the ICSP header pins to the EEPROM on the *Digital FX Pedal* PCB.

EEPROM pin 7 is disabled and connected to GND. Pins 1, 2, 3 are the address pins and are connected to Vcc or Vdd, depending on the application.

Modifying the PICkit 3

To enable the PICkit 3 to program the 24LC series of EEPROMs, TR3 (a diode) and R50 (a resistor) need to be removed from inside the PICkit 3. Crack open the case and locate the components. These are labelled on the PCB screen printing, as shown in Fig.1.

Desolder these, taking note of TR3's orientation and keep the parts in a safe place for replacing later on. The easiest way to do this is with a hot air rework station, gently heating the components while holding them with tweezers. However, you *can* also do it with a regular iron, by alternately heating the joints while holding it with tweezers, until the part comes loose.

PICkit 2 programmer emulator

The software to use the PICkit 3 to program the EEPROM can be downloaded here: **https://bit.ly/pe-may22-pk3**

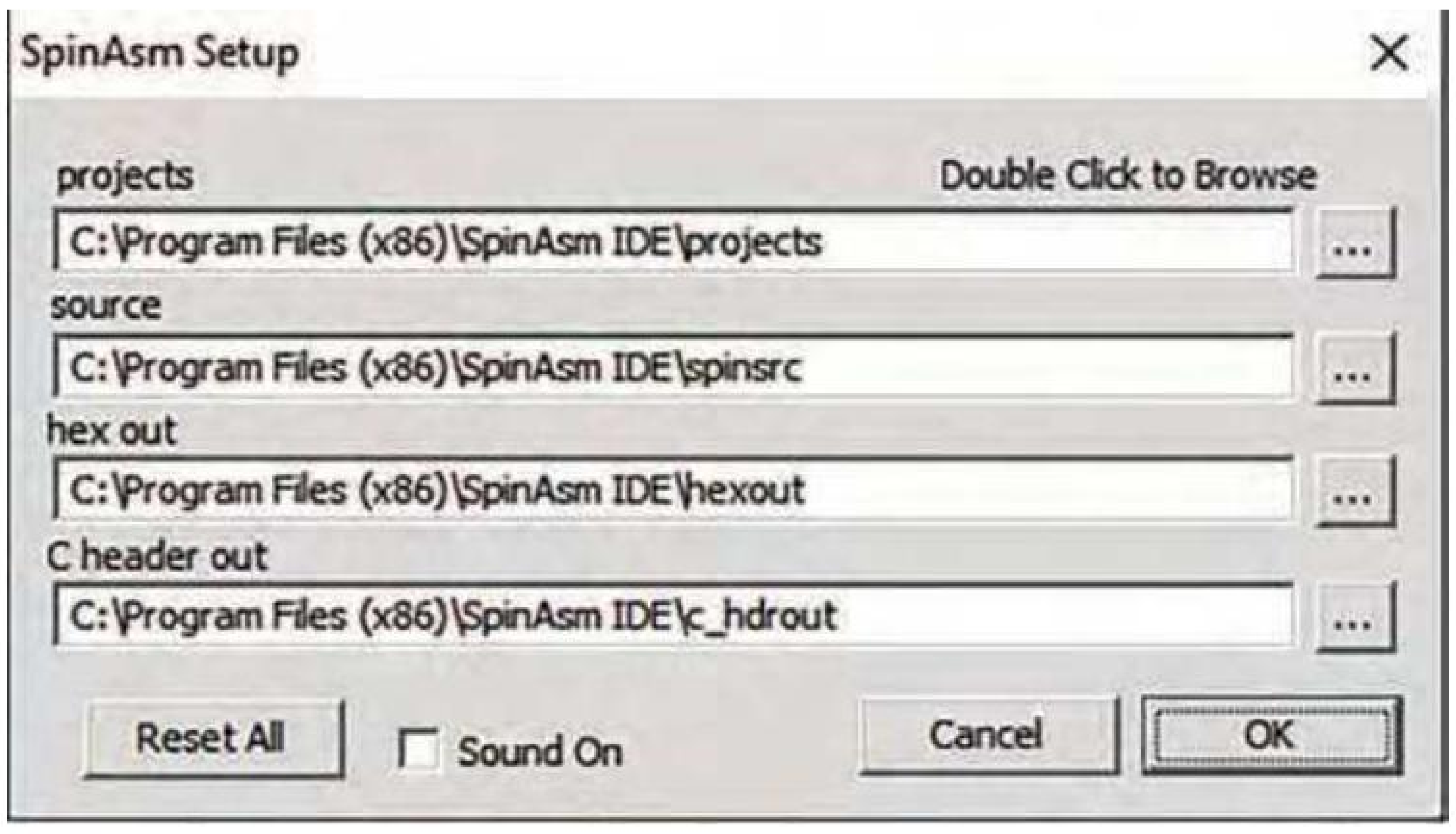
If you aren't sure how to install this software package, see the separate section below.

Before starting the PICkit 3 programmer, you need to connect the PICkit 3 to the computer. This so that the program will run correctly at startup.

Having installed the software linked above, navigate to **C:\Program Files (x86)\Microchip\PICkit 3 v3** and start the PICkit 3 application, or place a shortcut on your desktop and use that. The programming software will open, and state that the PICkit is connected (Screen8).

Under the Tools menu, select 'Download PICkit Operating System' (Screen9). This is the PICkit 2 emulator. Select the file **C:\Program Files (x86)\Microchip\PICkit 3 v3\PK3OSV020005.hex** (installed with the software; see Screen10) and the PICkit 3 will be loaded with the required firmware. Then, in the Device Family menu, select EEPROMS and 24LC (Screen11). Next, find the 24LC32A entry under the Device dropbox (Screen12).

Next, using the File menu, load the **Spin.hex** file located at **C:\Program Files (x86)\SpinAsm IDE\hexout\SC patches.hex** (or whatever name you saved it under).


SpinAsm Setup
Double Click to Browse
...
Reset All
☐ Sound On
Cancel
OK

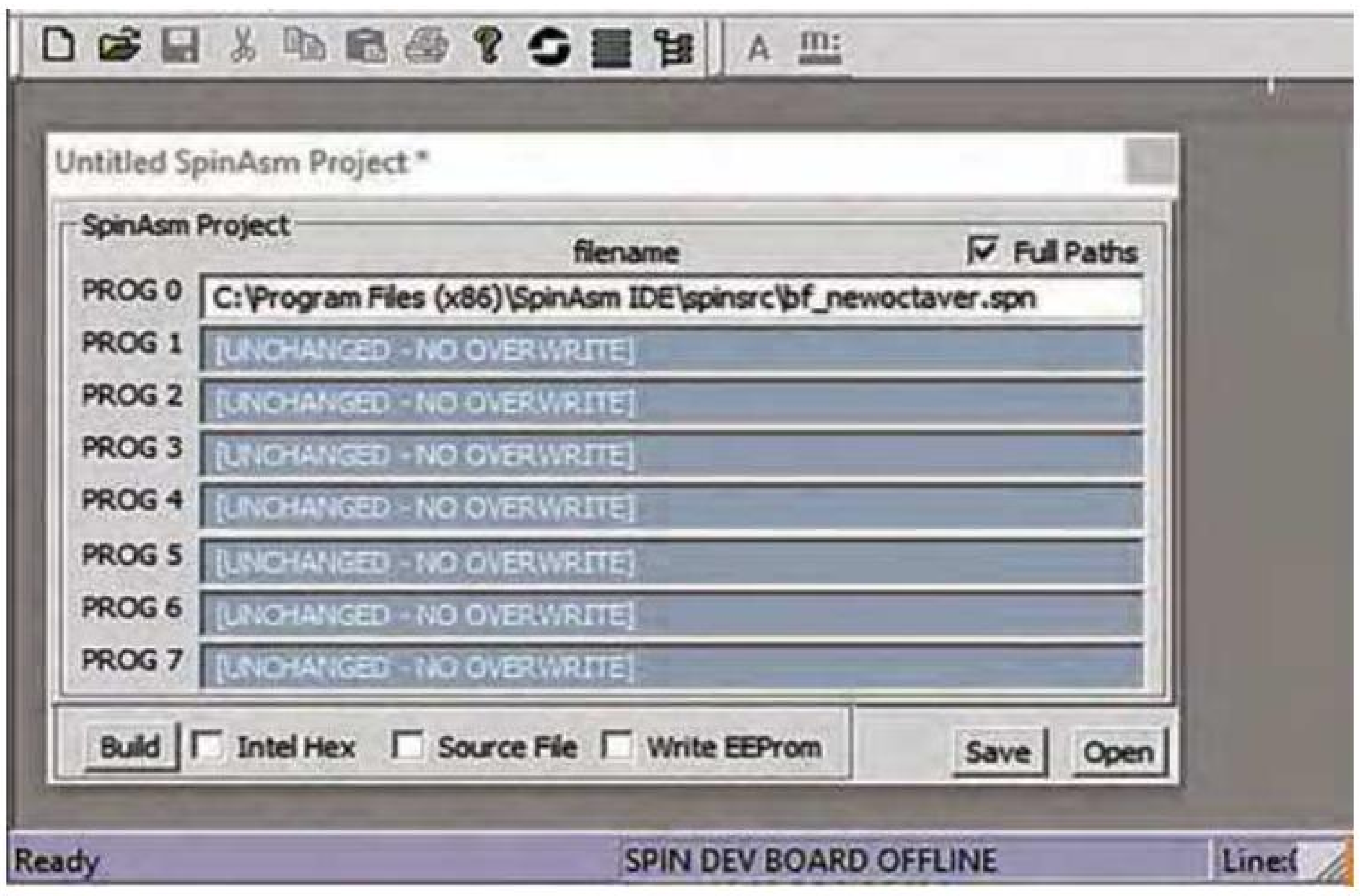
projects: C:\Program Files (x86)\SpinAsm IDE\projects

source: C:\Program Files (x86)\SpinAsm IDE\spinsrc

hex out: C:\Program Files (x86)\SpinAsm IDE\hexout

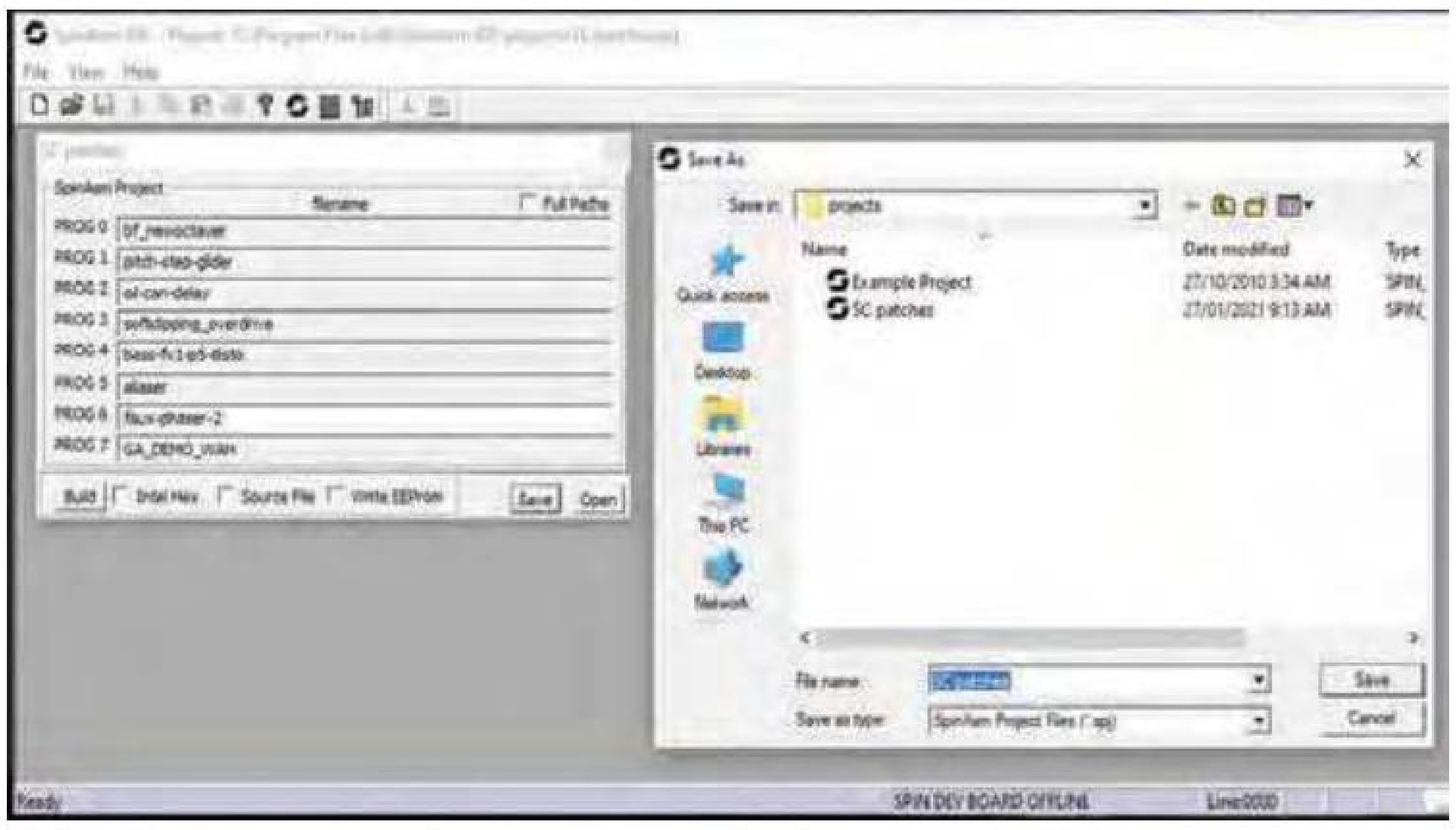
C header out: C:\Program Files (x86)\SpinAsm IDE\c_hdrout

Screen5: you can change the default folders where files are loaded and stored by the SpinASM, although we decided to stick with the defaults.


Untitled SpinAsm Project *
SpinAsm Project
filename
☑ Full Paths
PROG 1 [UNCHANGED - NO OVERWRITE]
PROG 2 [UNCHANGED - NO OVERWRITE]
PROG 3 [UNCHANGED - NO OVERWRITE]
PROG 4 [UNCHANGED - NO OVERWRITE]
PROG 5 [UNCHANGED - NO OVERWRITE]
PROG 6 [UNCHANGED - NO OVERWRITE]
PROG 7 [UNCHANGED - NO OVERWRITE]
Build ☐ Intel Hex ☐ Source File ☐ Write EEProm
Save Open
Ready
SPIN DEV BOARD OFFLINE
Line:(

PROG 0 C:\Program Files (x86)\SpinAsm IDE\spinsrc\bf_newoctaver.spn

Screen6: the SpinASM files have an extension of .spn, and here we have loaded the new octaver effect into the first slot, PROG 0.



Screen7: a standard file dialog is presented when you opt to save your project (.spj file). Note that we have loaded all eight slots with different effects. Choose a memorable file name.

Once this file has been loaded, the EEPROM can be programmed. First, make sure one of the first eight effects is selected so the FV-1 chip will not access the EEPROM during programming. Then connect the PICkit 3 to the ICSP header, with its triangle to pin 1, and switch on power to the Digital FX Pedal. Do not select the option of target power via the PICkit. Then click the 'Write' button to program the EEPROM – see Screen13.

Before closing the program, in the Tools menu, select the 'Revert to MPLAB mode' option to restore the PICkit 3 to normal operation, suitable for use with MPLAB (see Screen14).

When closing this program, it is not unusual to see an 'unhandled exception' dialog box appear, as shown in Screen15. Click 'Quit' to close it. The program may take a while to close; you might have to force close it using Windows Task Manager.

If you are finished programming, you can reinstall TR3 and R50 on the PICkit 3 board, to restore its full PIC programming function.

Catch 22

If an effects patch fills the entire 512 x 8-bit memory block, it must be placed in the last used PROG position. Otherwise, that effect will not work, as its data will be corrupted. The catch is that you won't know as the corrupted file will have similar ending values to the other patches. The hex files are easily viewed in the PICkit 3 Programmer software. Typical effects patches do not fill the entire 512 bytes, and the unused memory is filled with 00s and 11 at every 4th location.

So a corrupted file will not be evident until it is tested and found not to work. Swapping the non-working patch to the end of the list by reordering the PROG selections should solve this. It also means that you can only use one effects patch that fills the entire allocated memory section.

We found that the 'Faux-phaser-2' patch did not work when it was placed in PROG6 position. Moving it to the PROG7 (last) position made it work. We then realised that the code for this patch filled the full 512 bytes. When this patch was in PROG6, the 512 bytes were not completely filled with code, showing that it was corrupted. Note that each PROG entry has its own address range:

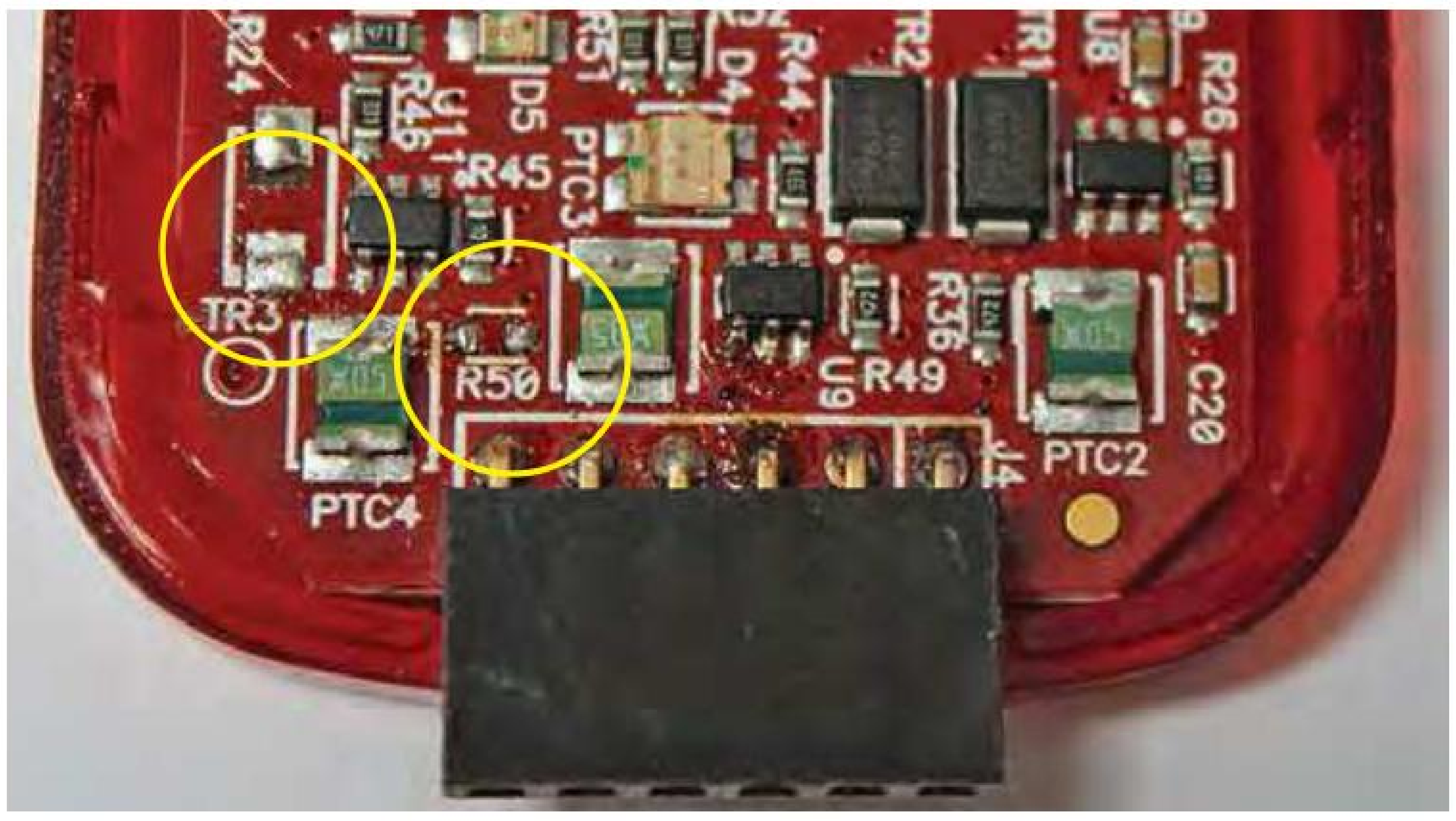
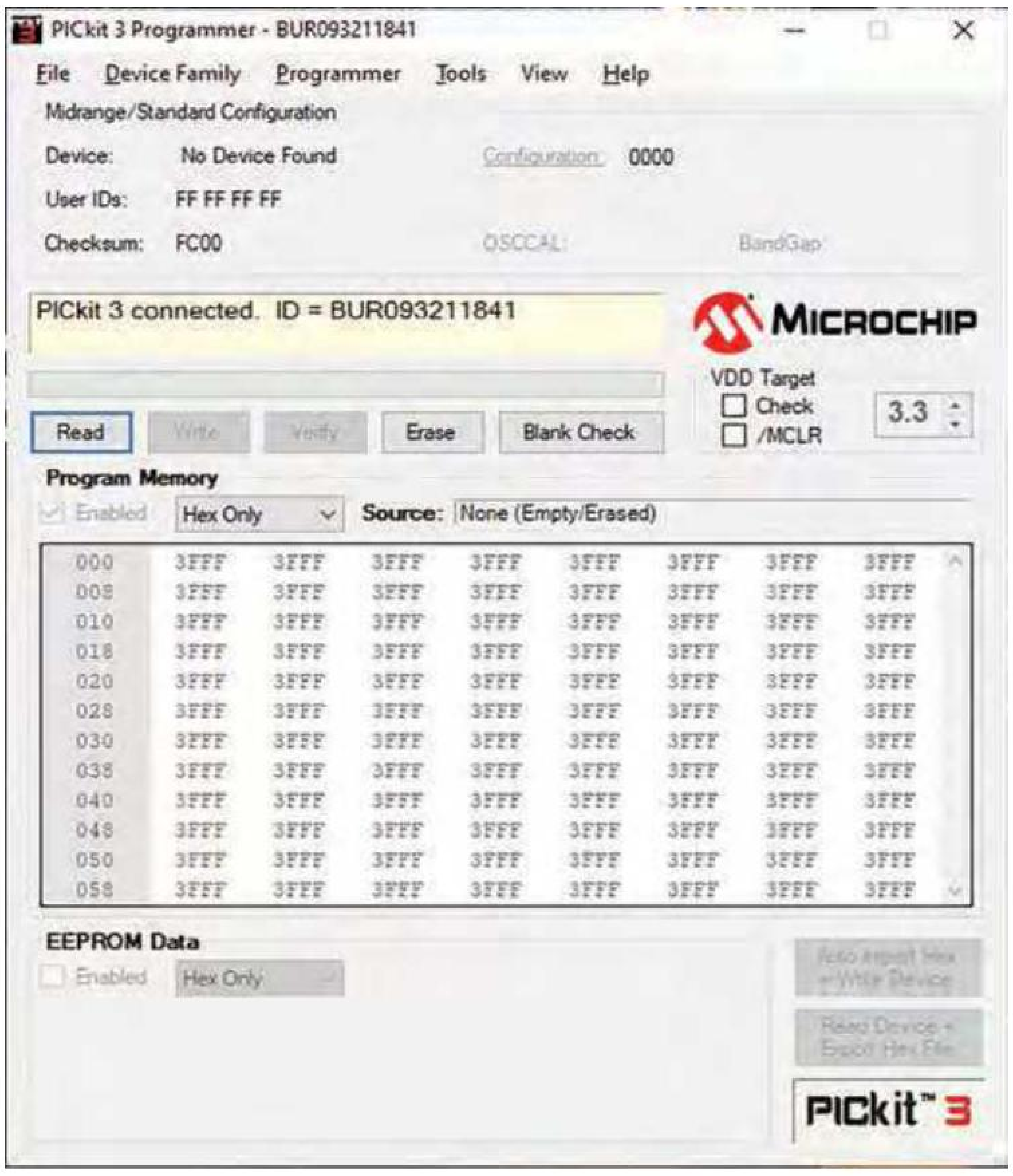

R24
R46
U1
D5
R45
PTC3
D4
R44
R2
TR1
U8
R26
TR3
R50
R36
U9
R49
C20
PTC4
PTC2

Fig.1: we temporarily removed two components from the PICkit 3: diode TR3 at far left, and resistor R50 just above the programming socket. These interfere with EEPROM programming. Keep the parts as you can reinstall them later if you want to turn the PICKit 3 back into a PIC programmer. Note the original orientation of TR3 (cathode stripe towards PTC4).



PICkit 3 Programmer - BUR093211841

Midrange/Standard Configuration

Device: No Device Found

Configuration: 0000

User IDs: FF FF FF FF

Checksum: FC00

PICkit 3 connected. ID = BUR093211841

VDD Target: 3.3

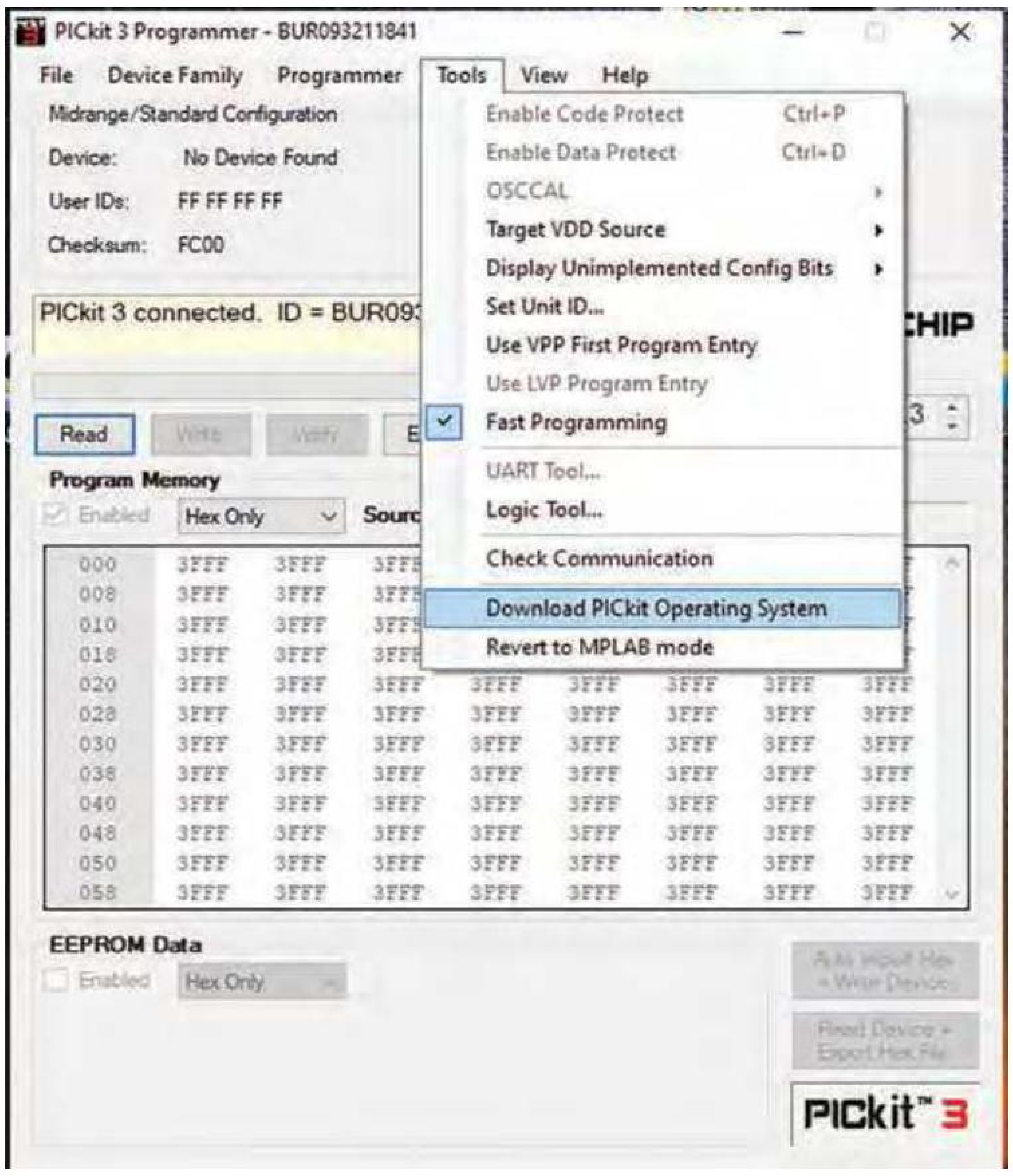
Program Memory: Hex Only; Source: None (Empty/Erased)

```
000  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF
008  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF
010  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF
018  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF
020  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF
028  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF
030  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF
038  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF
040  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF
048  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF
050  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF
058  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF  3FFF
```

EEPROM Data: Hex Only

File
Device Family
Programmer
Tools
View
Help
MICROCHIP
Read
Write
Verify
Erase
Blank Check
☐ Check
☐ /MCLR
Enabled
Auto Import Hex + Write Device
Read Device + Export Hex File
PICkit 3

Screen8: this version of the PICkit 3 programming software can program EEPROMs. Note the message in the yellow shaded box indicating that it has detected the hardware.



PICkit 3 Programmer - BUR093211841

Midrange/Standard Configuration

Device: No Device Found

User IDs: FF FF FF FF

Checksum: FC00

File
Device Family
Programmer
Tools
View
Help
Enable Code Protect Ctrl+P
Enable Data Protect Ctrl+D
OSCCAL
Target VDD Source
Display Unimplemented Config Bits
Set Unit ID...
Use VPP First Program Entry
Use LVP Program Entry
✓ Fast Programming
UART Tool...
Logic Tool...
Check Communication
Download PICkit Operating System
Revert to MPLAB mode
Read
Program Memory
Hex Only
EEPROM Data
PICkit 3

Screen9: use this menu option to load firmware into the PICkit 3 to emulate a PICkit 2. This is required to program the type of EEPROM we are using.

- PROG0: 000 to 1FF
- PROG1: 200 to 3FF
- PROG2: 400 to 5FF
- PROG3: 600 to 7FF
- PROG4: 800 to 9FF
- PROG5: A00 to BFF
- PROG6: C00 to DFF
- PROG7: E00 to FFF

Home-grown effects

Writing your own effects, or modifying existing effects patches, can be done using SpinAsm, or you can use a graphical programming package called SpinCAD Designer.

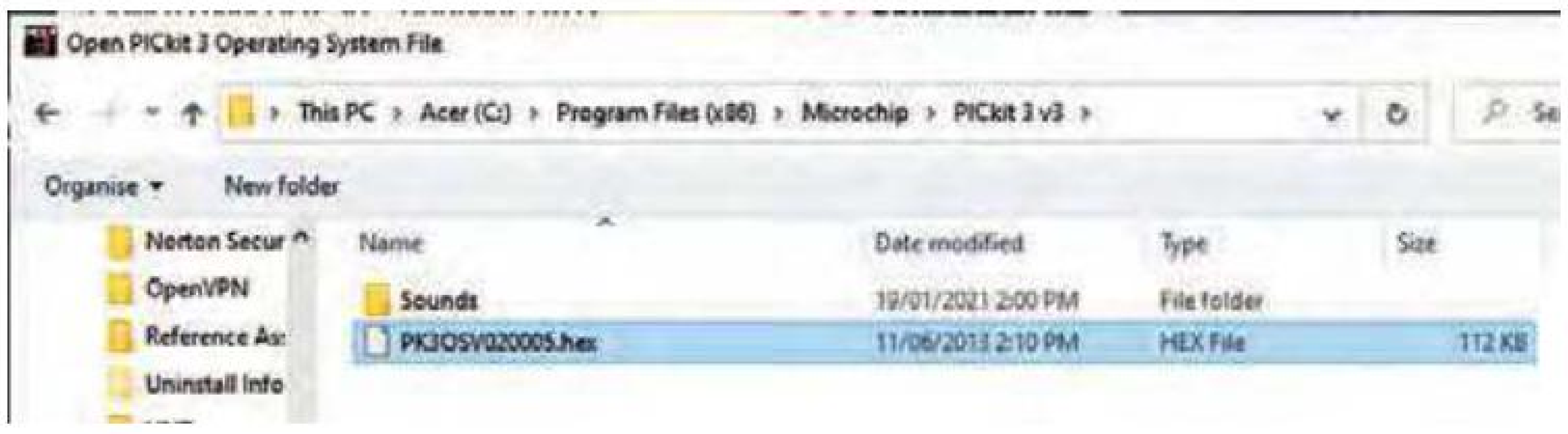
You will need to do some reading to be conversant with how to write the required code. You can also load some of the already-written effects patches to use as examples. The SPIN Semiconductor website has much of the required information. It is recommended that you read the knowledge base section: **https://bit.ly/pe-may22-spin**

This has information on the FV-1 architecture, instruction set, DSP basics and coding examples to list a few. You would also benefit from reading the data sheet and the user manual. These are found at **https://bit.ly/pe-may22-spin2** and **https://bit.ly/pe-may22-spin3**

SpinCAD Designer

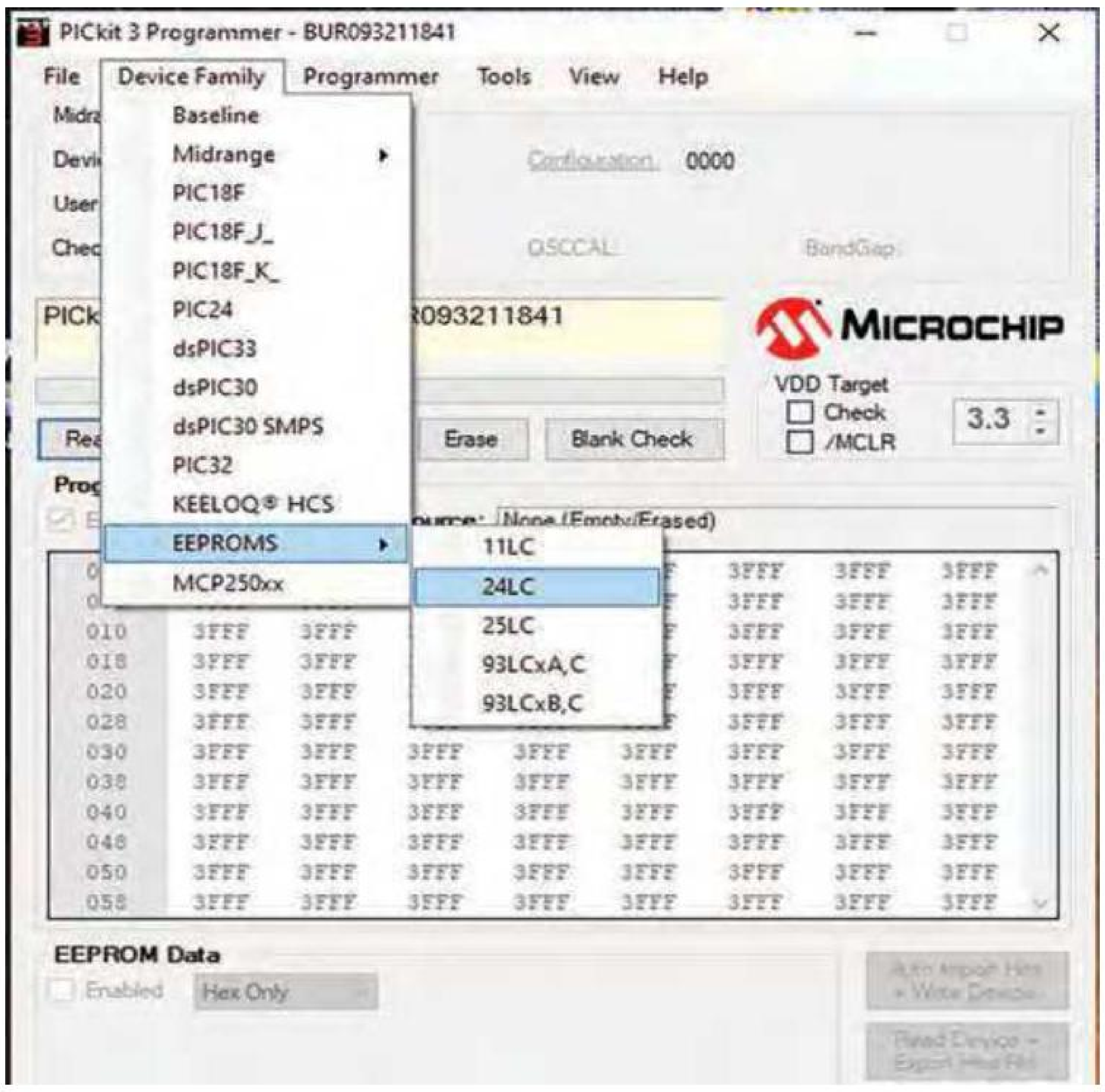
SpinCAD Designer is an open-source Java project which allows the creation of patches for the Spin FV-1 audio DSP chip using graphical instead of text coding. SpinCAD is available from **https://github.com/HolyCityAudio/SpinCAD-Designer**

If you need help installing this, see the separate section on installation.


Open PICkit 3 Operating System File
This PC › Acer (C:) › Program Files (x86) › Microchip › PICkit 3 v3 ›
Organise ▾
New folder
Norton Secur
OpenVPN
Reference As
Uninstall Info

Name	Date modified	Type	Size
Sounds	19/01/2021 2:00 PM	File folder	
PK3OSV020005.hex	11/06/2013 2:10 PM	HEX File	112 KB

Screen10: having selected the option shown in Screen9, the next step is to find the file shown here, This file is included with the software download and should be on your computer in the location described in the text.


PICkit 3 Programmer - BUR093211841
File
Device Family
Programmer
Tools
View
Help
Baseline
Midrange
PIC18F
PIC18F_J_
PIC18F_K_
PIC24
dsPIC33
dsPIC30
dsPIC30 SMPS
PIC32
KEELOQ® HCS
EEPROMS
MCP250xx
11LC
24LC
25LC
93LCxA,C
93LCxB,C
Configuration:
OSCCAL:
BandGap:
MICROCHIP
VDD Target
Erase
Blank Check
EEPROM Data
Enabled
Hex Only
Auto Import Hex + Write Device
Read Device + Export Hex File

Configuration: 0000

093211841

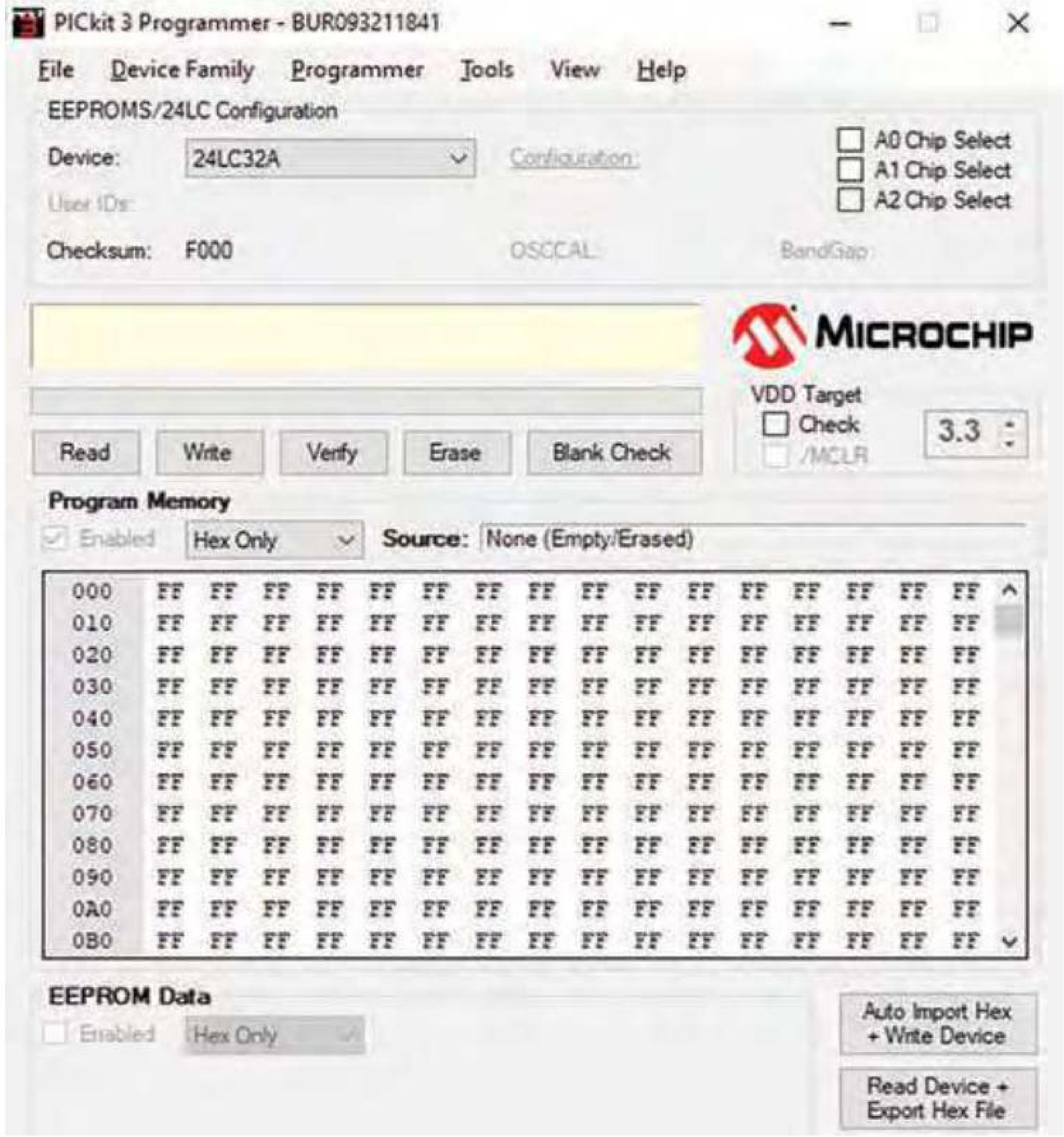
VDD Target ☐ Check ☐ /MCLR 3.3

Source: None (Empty/Erased)

```
030   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF
038   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF
040   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF
048   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF
050   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF
058   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF   3FFF
```

Screen11: with the PICkit 2 emulator loaded, select the 24LC EEPROM device from the Device Family menu.

Navigate to the SpinCAD Designer folder and open the Spin CAD-designer-1027 jar file. This will start SpinCAD Designer. Note that the patches folder for SpinCAD Designer includes many effects patch files that have already been written, in a compressed format. These are included as SpinCAD files as well, as SpinAsm files. These can be used as examples to get you started.


PICkit 3 Programmer - BUR093211841
File
Device Family
Programmer
Tools
View
Help
EEPROMS/24LC Configuration
Configuration:
User IDs:
OSCCAL:
BandGap:
MICROCHIP
Read
Write
Verify
Erase
Blank Check
Program Memory
Enabled
EEPROM Data
Enabled
Hex Only
Auto Import Hex + Write Device
Read Device + Export Hex File

Device: 24LC32A

☐ A0 Chip Select
☐ A1 Chip Select
☐ A2 Chip Select

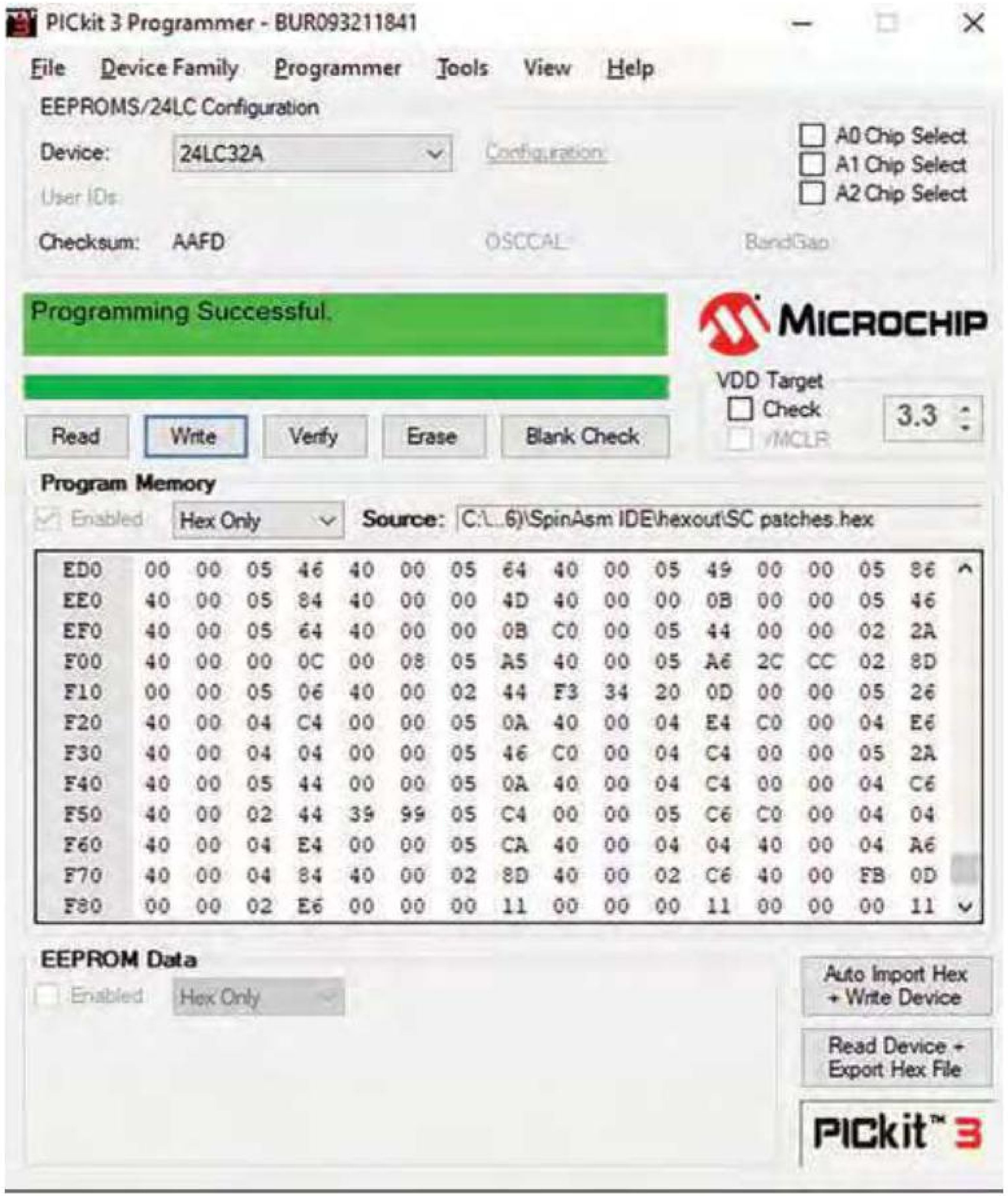
Checksum: F000

VDD Target ☐ Check ☐ /MCLR 3.3

Program Memory: ☑ Enabled Hex Only Source: None (Empty/Erased)

```
000   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
010   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
020   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
030   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
040   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
050   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
060   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
070   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
080   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
090   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
0A0   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
0B0   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
```

Screen12: you can now select 24LC32A from the Device dropdown at upper left, then use the File menu to open the EEPROM HEX file you generated earlier.


PICkit 3 Programmer - BUR093211841
File
Device Family
Programmer
Tools
View
Help
EEPROMS/24LC Configuration
Configuration:
User IDs:
OSCCAL:
BandGap:
MICROCHIP
Read
Write
Verify
Erase
Blank Check
Program Memory
Enabled
EEPROM Data
Enabled
Hex Only
Auto Import Hex + Write Device
Read Device + Export Hex File
PICkit™ 3

Device: 24LC32A

☐ A0 Chip Select
☐ A1 Chip Select
☐ A2 Chip Select

Checksum: AAFD

Programming Successful.

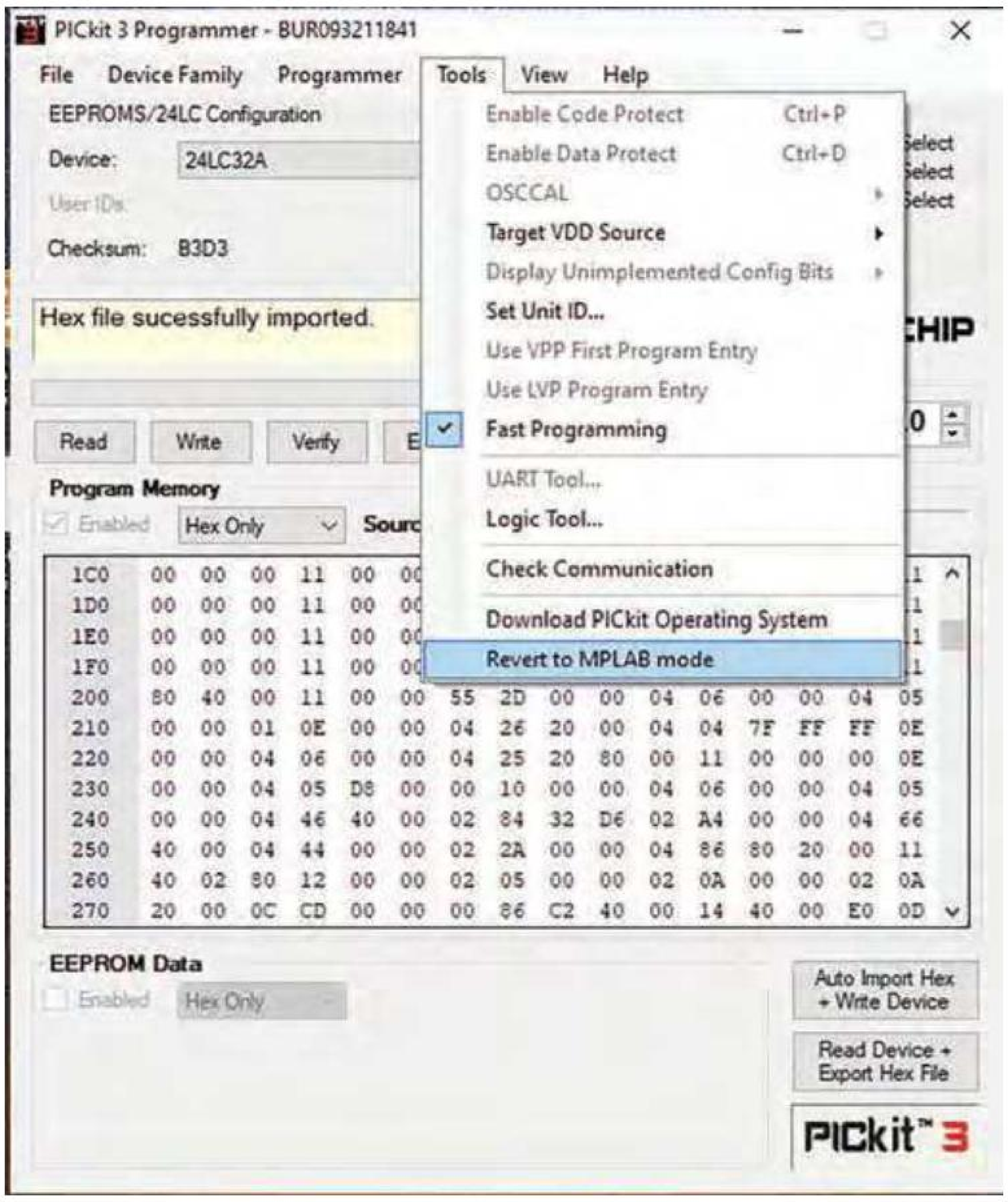
VDD Target ☐ Check ☐ /MCLR 3.3

Program Memory: ☑ Enabled Hex Only Source: C:\...6)\SpinAsm IDE\hexout\SC patches.hex

```
ED0   00 00 05 46 40 00 05 64 40 00 05 49 00 00 05 86
EE0   40 00 05 84 40 00 00 4D 40 00 00 0B 00 00 05 46
EF0   40 00 05 64 40 00 00 0B C0 00 05 44 00 00 02 2A
F00   40 00 00 0C 00 08 05 A5 40 00 05 A6 2C CC 02 8D
F10   00 00 05 06 40 00 02 44 F3 34 20 0D 00 00 05 26
F20   40 00 04 C4 00 00 05 0A 40 00 04 E4 C0 00 04 E6
F30   40 00 04 04 00 00 05 46 C0 00 04 C4 00 00 05 2A
F40   40 00 05 44 00 00 05 0A 40 00 04 C4 00 00 04 C6
F50   40 00 02 44 39 99 05 C4 00 00 05 C6 C0 00 04 04
F60   40 00 04 E4 00 00 05 CA 40 00 04 04 40 00 04 A6
F70   40 00 04 84 40 00 02 8D 40 00 02 C6 40 00 FB 0D
F80   00 00 02 E6 00 00 00 11 00 00 00 11 00 00 00 11
```

Screen13: with the programmer connected to the powered Digital FX Pedal, the Device selected and the HEX file loaded, click the Write button to program the effects into the EEPROM chip. You should be greeted with the Programming Successful message on a green background. Unplug the programmer and test all the effects to check that they are working as expected.

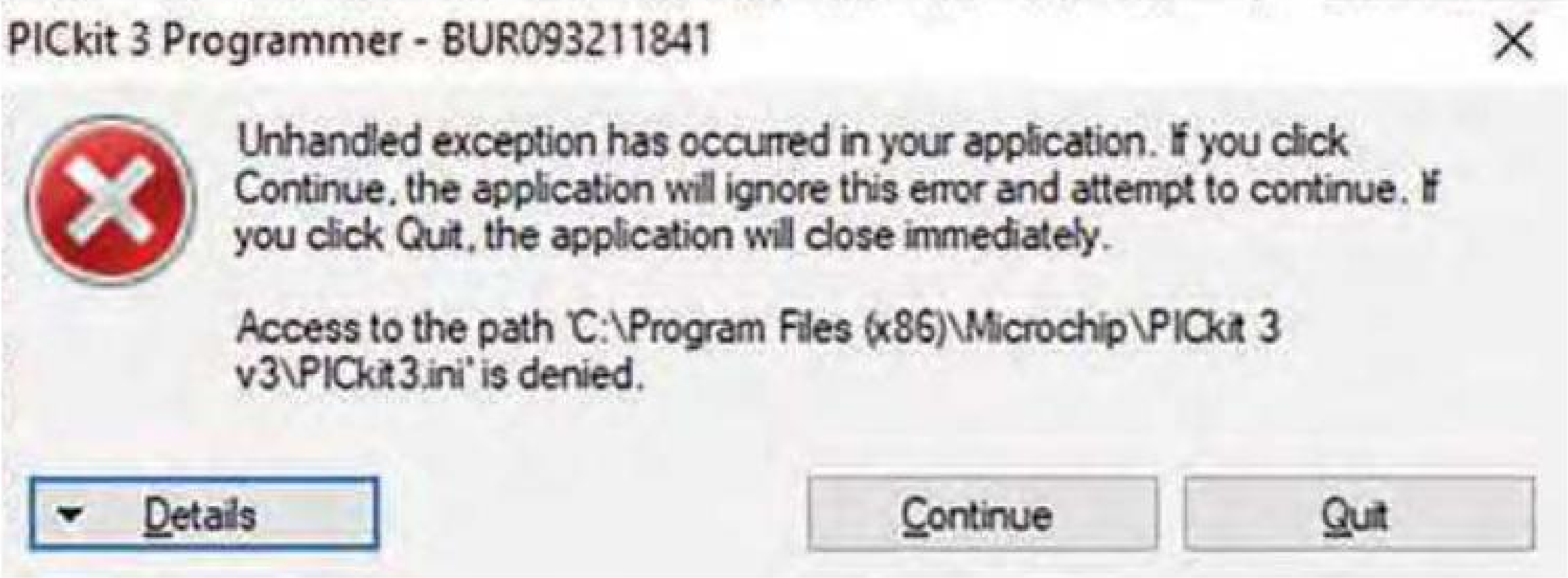
The example shown in Screen16 is a test patch written for a ring modulator in Patch0. It includes a 6-band equaliser and ring modulator adjusted with Pot 0.


PICkit 3 Programmer - BUR093211841
File
Device Family
Programmer
Tools
View
Help
EEPROMS/24LC Configuration
Device:
24LC32A
User IDs:
Checksum:
B3D3
Enable Code Protect Ctrl+P
Enable Data Protect Ctrl+D
OSCCAL
Target VDD Source
Display Unimplemented Config Bits
Set Unit ID...
Use VPP First Program Entry
Use LVP Program Entry
Fast Programming
UART Tool...
Logic Tool...
Check Communication
Download PICkit Operating System
Revert to MPLAB mode
Read
Write
Verify
Program Memory
Enabled
Hex Only
EEPROM Data
Auto Import Hex + Write Device
Read Device + Export Hex File
PICkit™ 3

Hex file sucessfully imported.

```
1C0  00 00 00 11 00 0                                   1
1D0  00 00 00 11 00 0                                   1
1E0  00 00 00 11 00 0                                   1
1F0  00 00 00 11 00 0                                   1
200  80 40 00 11 00 00 55 2D 00 00 04 06 00 00 04 05
210  00 00 01 0E 00 00 04 26 20 00 04 04 7F FF FF 0E
220  00 00 04 06 00 00 04 25 20 80 00 11 00 00 00 0E
230  00 00 04 05 D8 00 00 10 00 00 04 06 00 00 04 05
240  00 00 04 46 40 00 02 84 32 D6 02 A4 00 00 04 66
250  40 00 04 44 00 00 02 2A 00 00 04 86 80 20 00 11
260  40 02 80 12 00 00 02 05 00 00 02 0A 00 00 02 0A
270  20 00 0C CD 00 00 00 86 C2 40 00 14 40 00 E0 0D
```

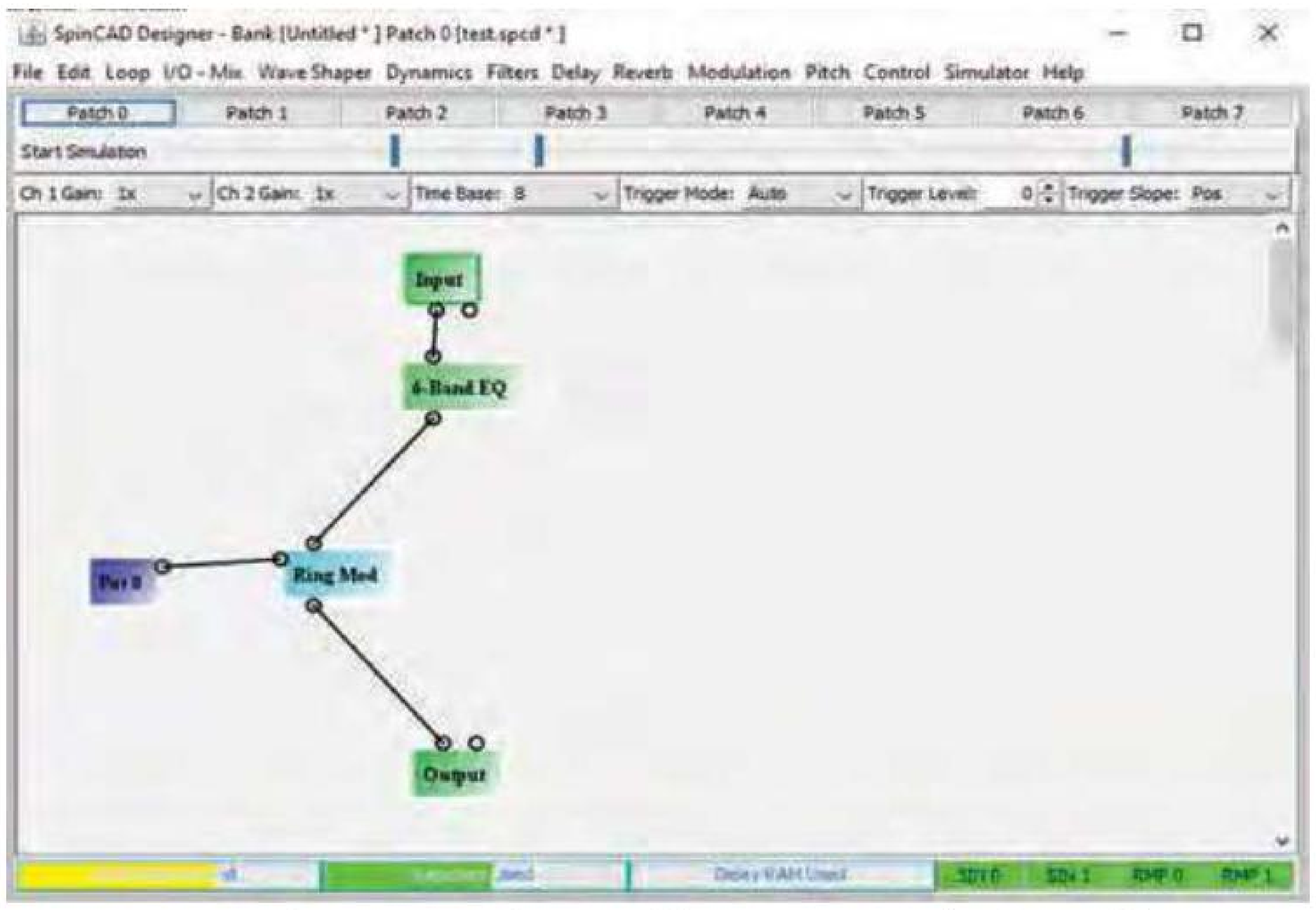
Screen14 (left): after you have finished your EEPROM programming, if you want to revert the PICkit 3 to normal operation, in addition to refitting the two components removed earlier, you will have to select this menu option to re-load its original firmware.


PICkit 3 Programmer - BUR093211841
Details
Continue
Quit

Unhandled exception has occurred in your application. If you click Continue, the application will ignore this error and attempt to continue. If you click Quit, the application will close immediately.

Access to the path 'C:\Program Files (x86)\Microchip\PICkit 3 v3\PICkit3.ini' is denied.

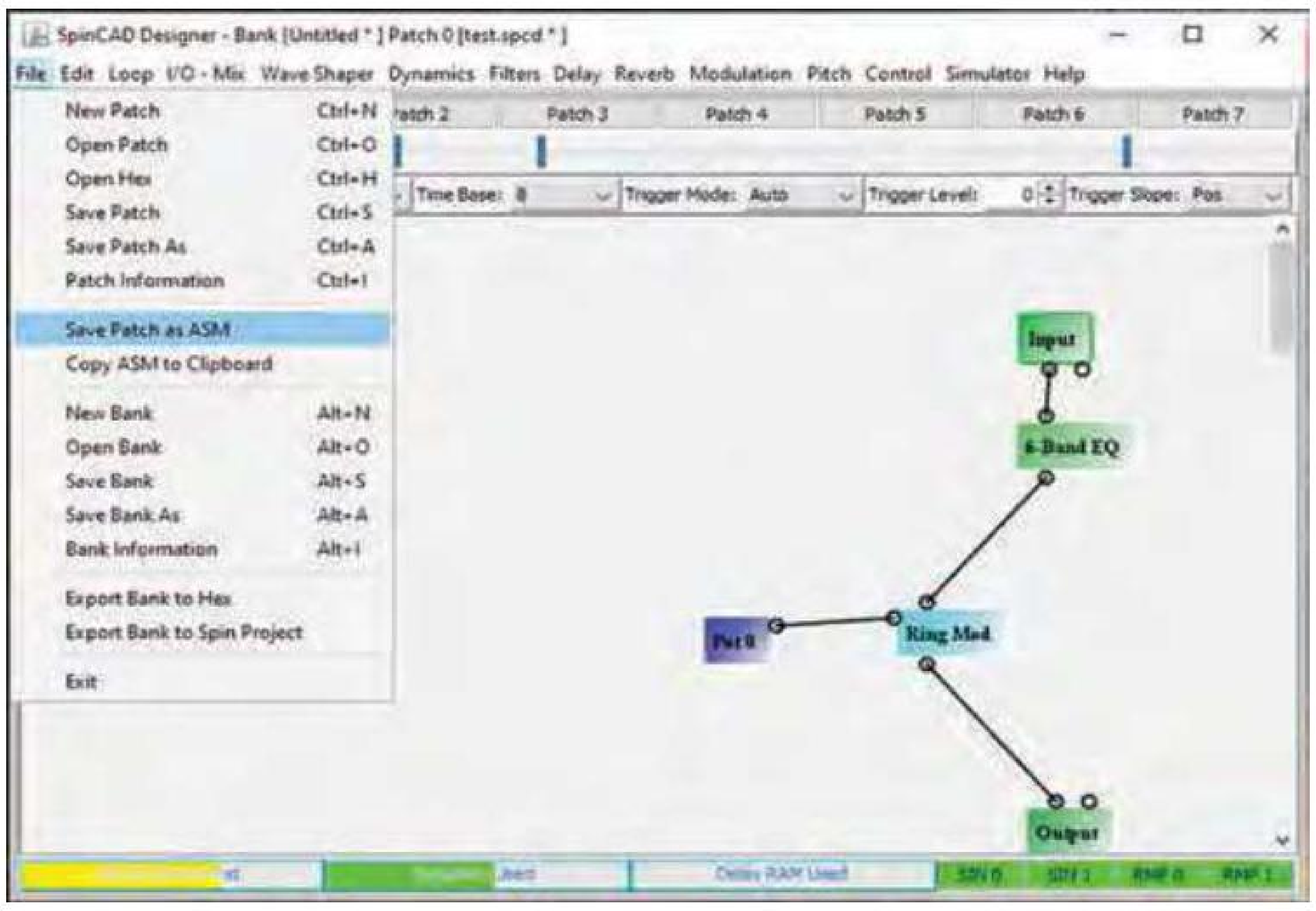
**Screen15: do not be surprised if you get this error message upon closing the programming software. Click Quit.
You might need to launch Task Manager (eg, by pressing Ctrl+Alt+Del) to kill the process if it lingers.**


SpinCAD Designer - Bank [Untitled *] Patch 0 [test.spcd *]
File Edit Loop I/O - Mix Wave Shaper Dynamics Filters Delay Reverb Modulation Pitch Control Simulator Help
Patch 0
Patch 1
Patch 2
Patch 3
Patch 4
Patch 5
Patch 6
Patch 7
Start Simulation
Input
6-Band EQ
Pot 0
Ring Mod
Output

Screen16: SpinCAD Designer allows you to design effects patches without having to write assembly language code. The graphical designer is easy to use, and once you know what you are doing, you can create an effect very quickly indeed.

It took me only a few minutes to create, and probably is not a very good effect, but it does show that the graphical program is very useful and effective for developing an effects patch.

Once you have created a patch, it can be saved as an assembler file and then loaded into SpinAsm and converted to the Intel hex format using the 'Save Patch as ASM' option in the File menu (see Screen17).


SpinCAD Designer - Bank [Untitled *] Patch 0 [test.spcd *]
File Edit Loop I/O - Mix Wave Shaper Dynamics Filters Delay Reverb Modulation Pitch Control Simulator Help
New Patch Ctrl+N
Open Patch Ctrl+O
Open Hex Ctrl+H
Save Patch Ctrl+S
Save Patch As Ctrl+A
Patch Information Ctrl+I
Save Patch as ASM
Copy ASM to Clipboard
New Bank Alt+N
Open Bank Alt+O
Save Bank Alt+S
Save Bank As Alt+A
Bank Information Alt+I
Export Bank to Hex
Export Bank to Spin Project
Exit
Input
6-Band EQ
Pot 0
Ring Mod
Output

Screen17: once you have created your effect in SpinCAD Designer, select the 'Save Patch as ASM' option to get a file that you can program into the Digital FX Pedal using the procedure described in this article. It's also a good idea to use the 'Save Patch' option to save it in a format that will allow you to make changes in future!

Digital FX Unit build options

There are two choices to make when building this project.

1) Effects selection device
As explained last month, you need to choose which type of device you want to use to make effects selections: either a (possibly hard-to-source) 4-bit BCD switch, or a potentiometer/PIC combination, and from there choose the relevant PCB.

2) EEPROM programming
This month, we explained the method for programming the EEPROM. While it is a somewhat involved process, it is not actually that difficult, but we would not recommend it for beginners or those new to device programming with PICkits.

If you are happy with the default effects and/or hand-programming the EEPROM is not for you then pre-programmed EEPROMs are available from the *PE PCB Service* (see the May 2022 section). We are also selling the pre-programmed PIC for the potentiometer effects selection option (see above).

PICkit 2, 3 and 4
You will have noticed that we reference PICkit 2 and 3 to program the EEPROM. While they are no longer sold by Microchip, they are easy to buy used from eBay; typical prices are around £20. Do ensure you buy a Microchip-branded programmer and not a clone – they are often made to 'look' similar.

We do not recommend using a PICkit 4 to program the project's EEPROM.

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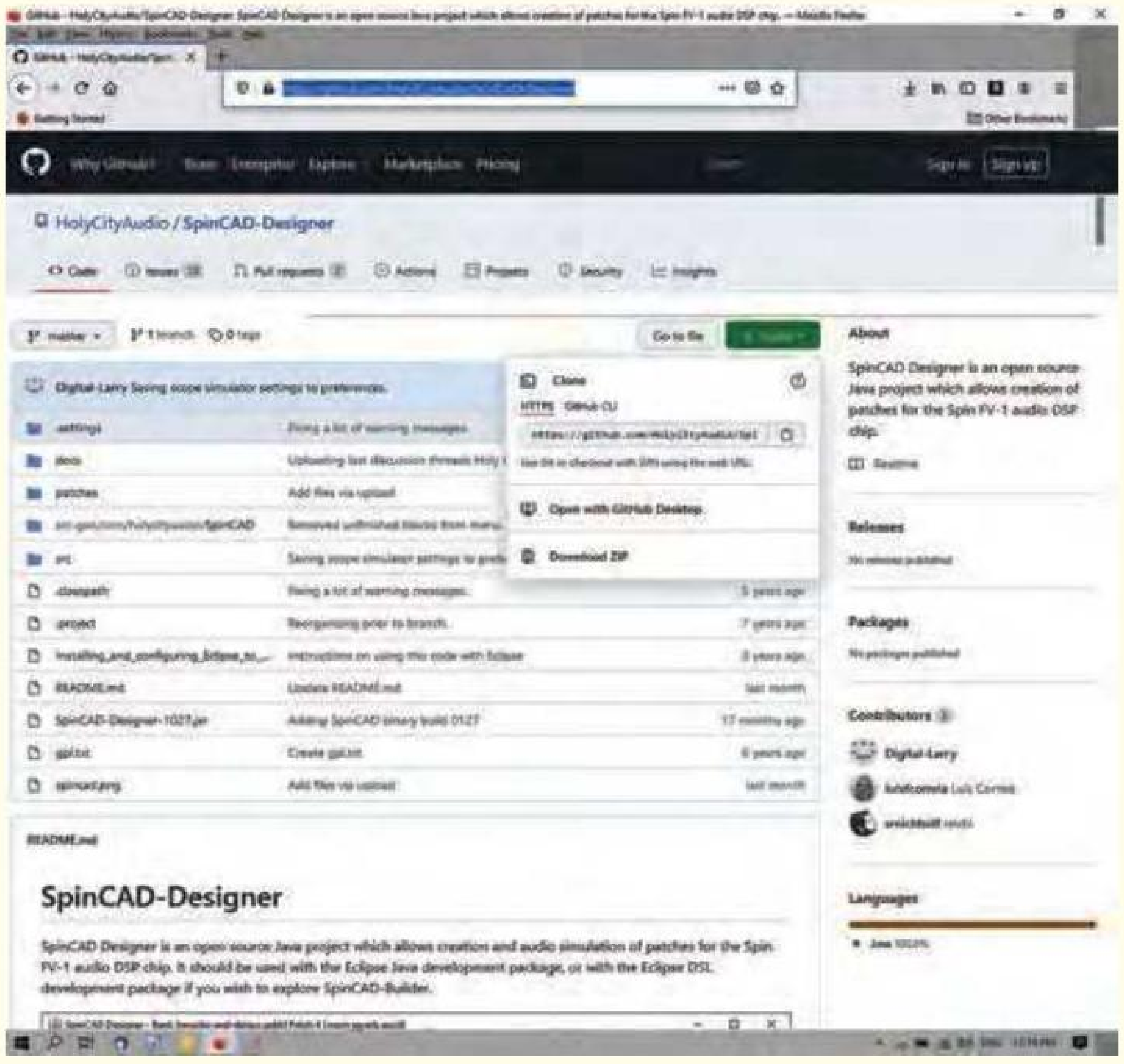
Installing SpinCAD Designer

You can download SpinCAD from: **https://github.com/HolyCityAudio/SpinCAD-Designer**

Click the green 'download code' button towards the upper right-hand corner of the page (see Screen18), then select 'Download ZIP'. Having downloaded the file, extract its contents to a suitable directory such as: **C:\Program Files\SpinCad Designer**



Screen18: you need to extract the SpinCAD Designer software zip before you can use it. You can accept the default destination, as shown here, or alter it before continuing.

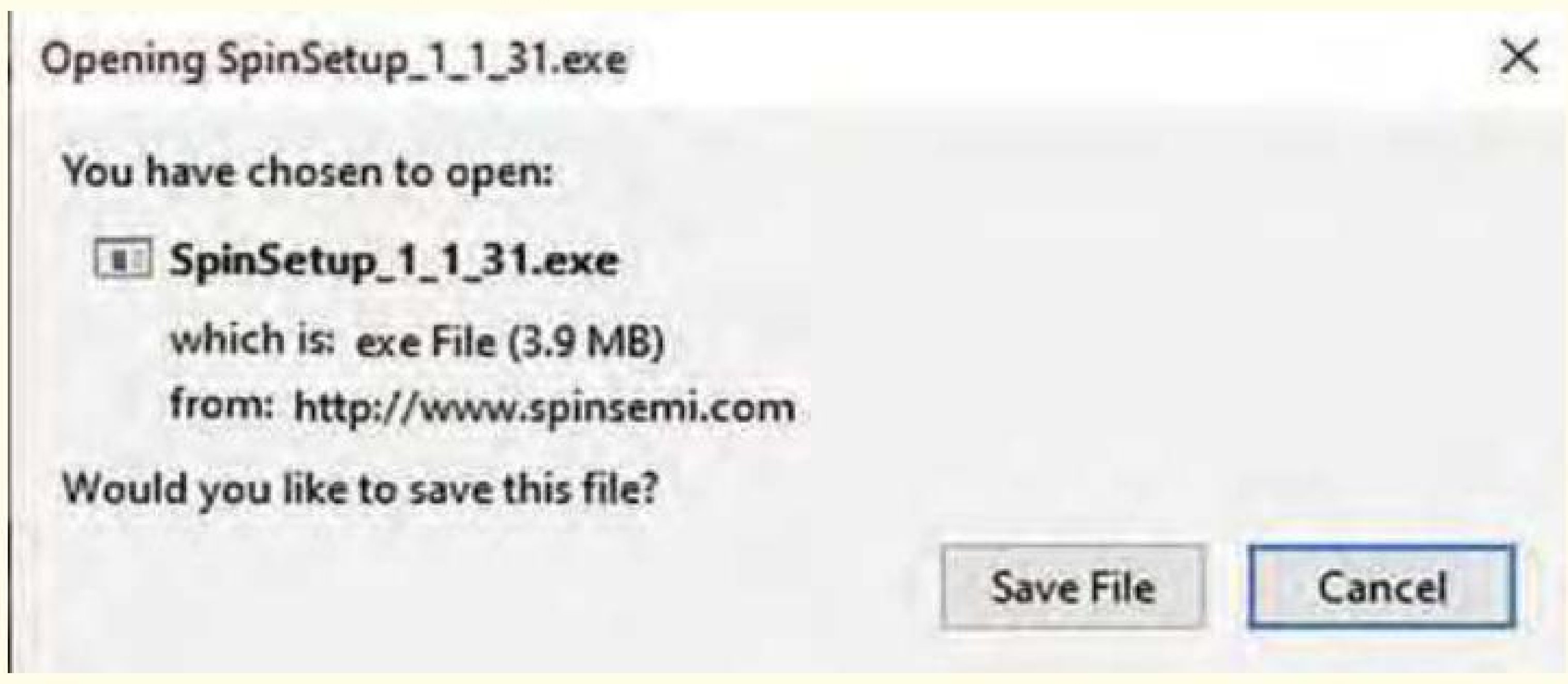
To run SpinCAD, you will need the Java Runtime Environment JRE/JDK 1.8 or later installed. You can get this from: **www.java.com/en/download/**

After downloading Java, run the executable file and agree to allow it to make changes to your device. Click through the following steps to install the Java runtime environment.

Now you can navigate to the folder where you extracted SpinCAD Designer earlier, and launch the Spin CAD-designer-1027 jar file.

Installing SpinAsm

When you click on (or type in) the link to download SpinAsm, you might get a dialog box like the one shown in Screen 19.



Opening SpinSetup_1_1_31.exe

You have chosen to open:

SpinSetup_1_1_31.exe

which is: exe File (3.9 MB)

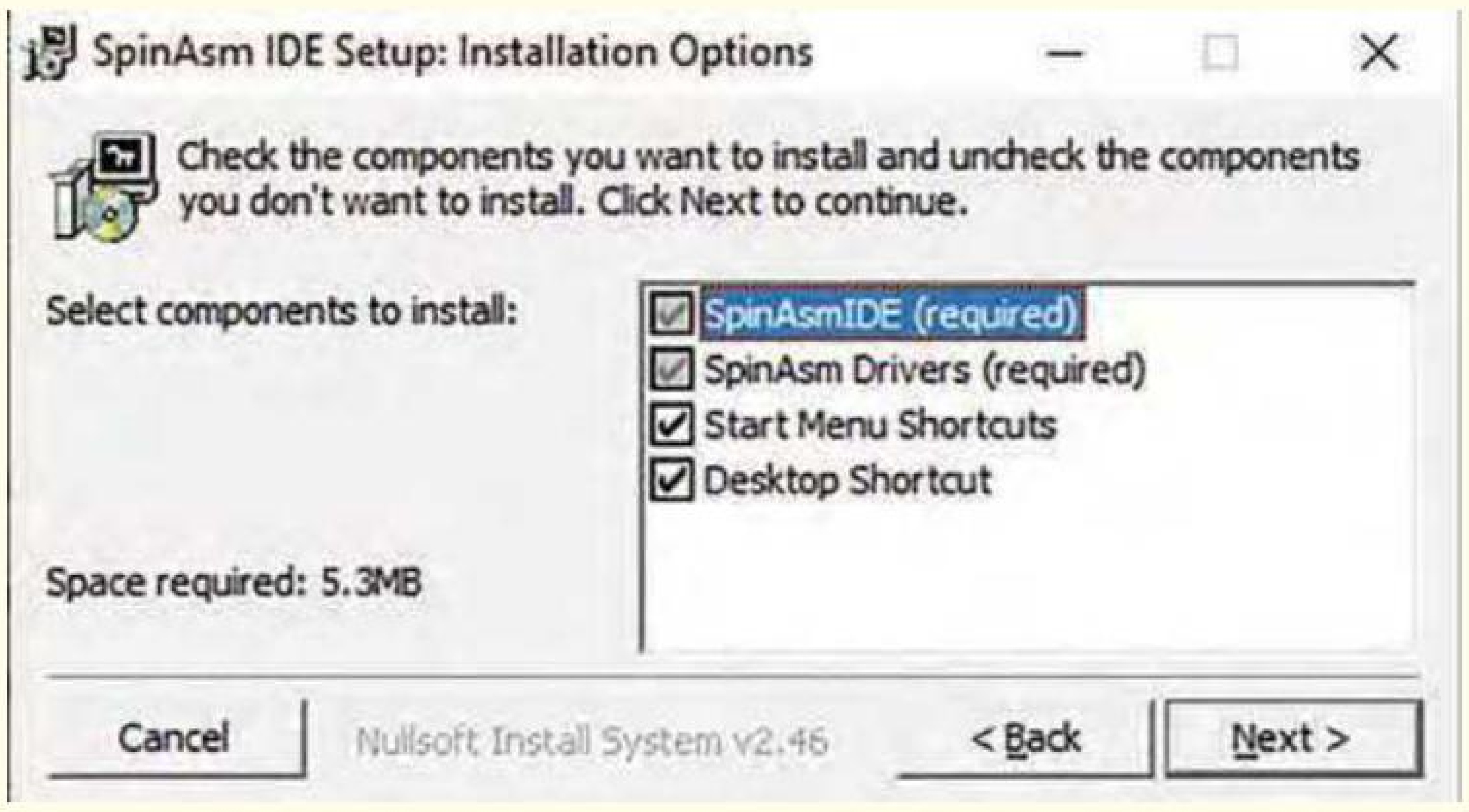
from: http://www.spinsemi.com

Would you like to save this file?

Screen19: when you click the link to download Spin, depending on what web browser you are using, you will probably be faced with a save dialog something like this. You will need to click 'Save File' and allow it to download before launching the installer.

Select 'Save File', then once it has downloaded, open it. It might ask you whether you want this app (from an unknown source) to make changes to your computer.

Select 'Yes', then agree to the terms and conditions and select the standard setup option (Screen20).



SpinAsm IDE Setup: Installation Options

Check the components you want to install and uncheck the components you don't want to install. Click Next to continue.

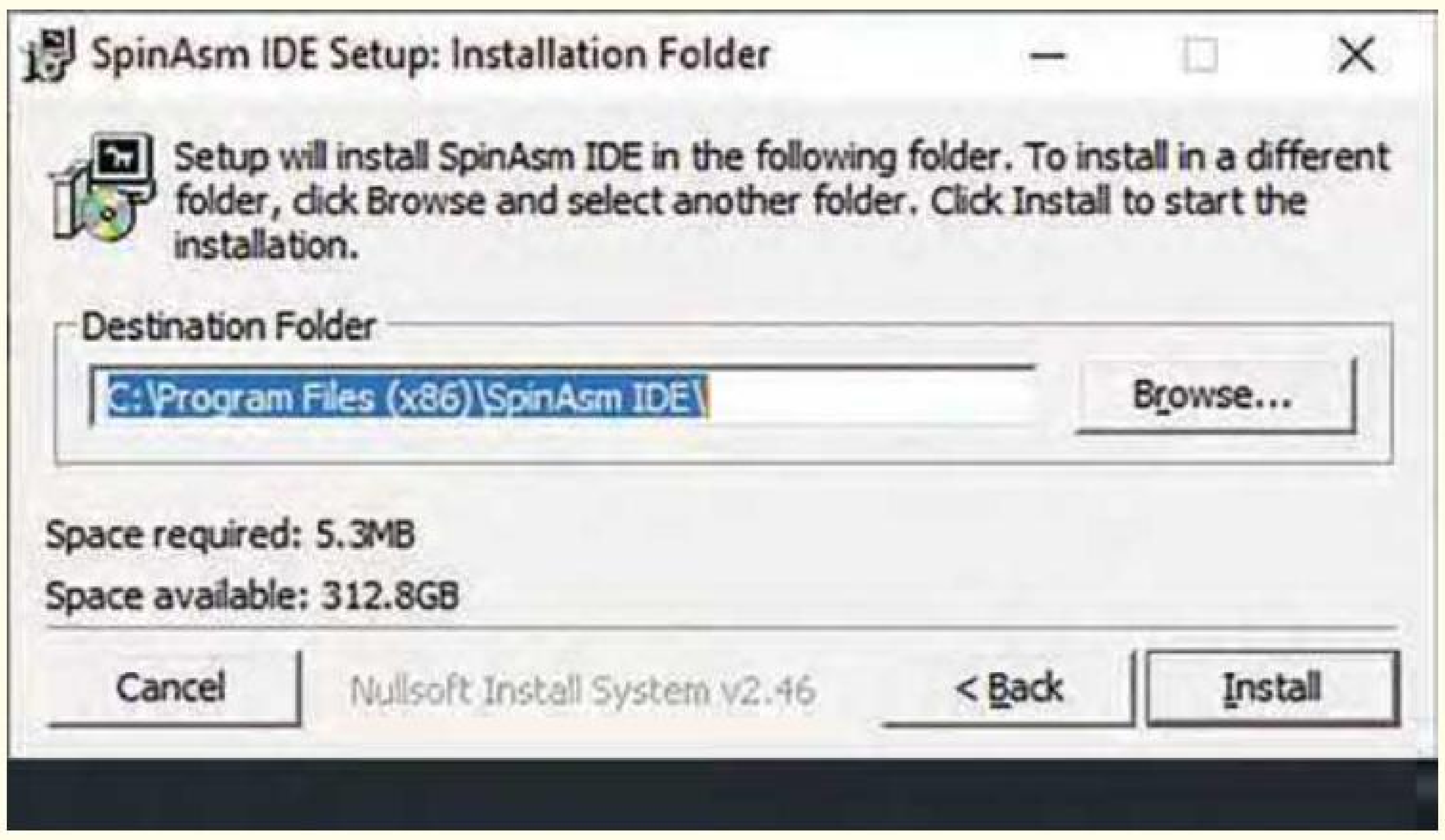
Select components to install:

☑ SpinAsmIDE (required)
☑ SpinAsm Drivers (required)
☑ Start Menu Shortcuts
☑ Desktop Shortcut

Space required: 5.3MB

Screen20: the default options to install SpinAsm IDE will suit most users.

Click 'Next' to continue, then click 'Install' (Screen21).



SpinAsm IDE Setup: Installation Folder

Setup will install SpinAsm IDE in the following folder. To install in a different folder, click Browse and select another folder. Click Install to start the installation.

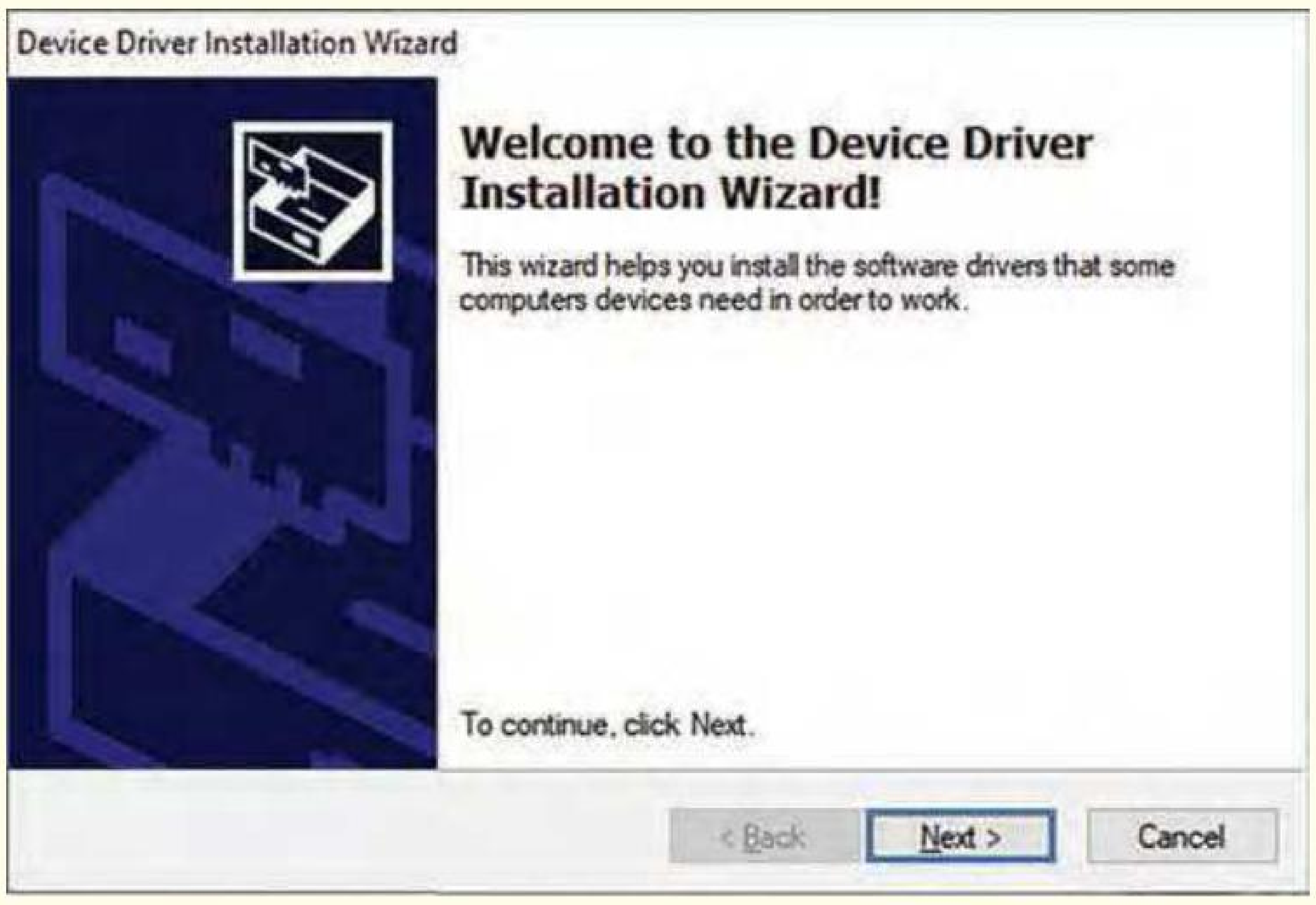
Destination Folder

C:\Program Files (x86)\SpinAsm IDE\

Space required: 5.3MB
Space available: 312.8GB

Screen21: you can change the SpinAsm IDE installation folder, but we left it at the default.

When you are prompted to install the driver (Screen22), click 'Next', then 'Finish' (Screen23) and installation is complete.



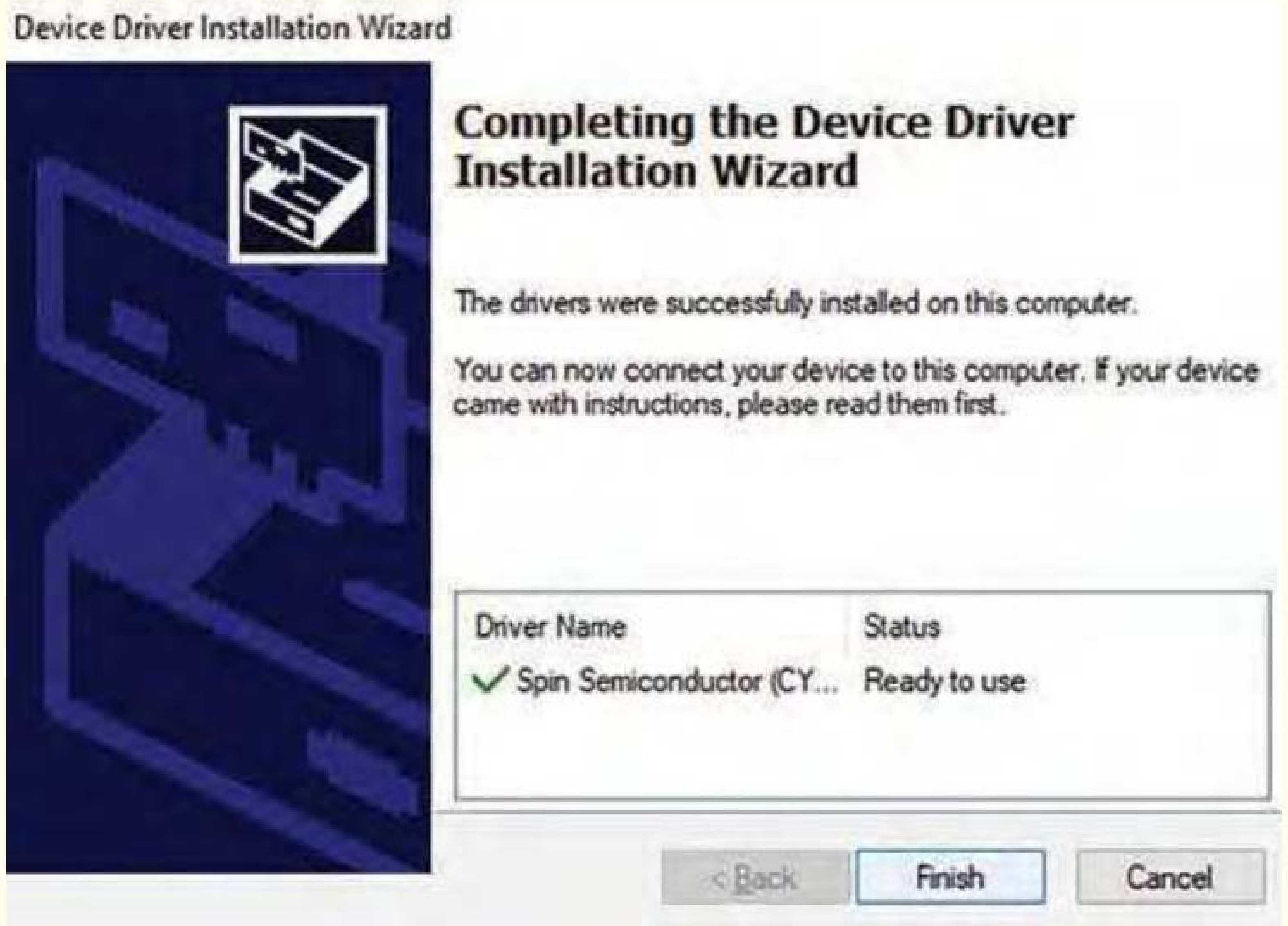
Device Driver Installation Wizard

Welcome to the Device Driver Installation Wizard!

This wizard helps you install the software drivers that some computers devices need in order to work.

To continue, click Next.

Screen22: as part of the SpinAsm installation, you will also need to install the SpinAsm drivers, which will require you to click through some more permission dialogs.



Device Driver Installation Wizard

Completing the Device Driver Installation Wizard

The drivers were successfully installed on this computer.

You can now connect your device to this computer. If your device came with instructions, please read them first.

Driver Name	Status
✓ Spin Semiconductor (CY...	Ready to use

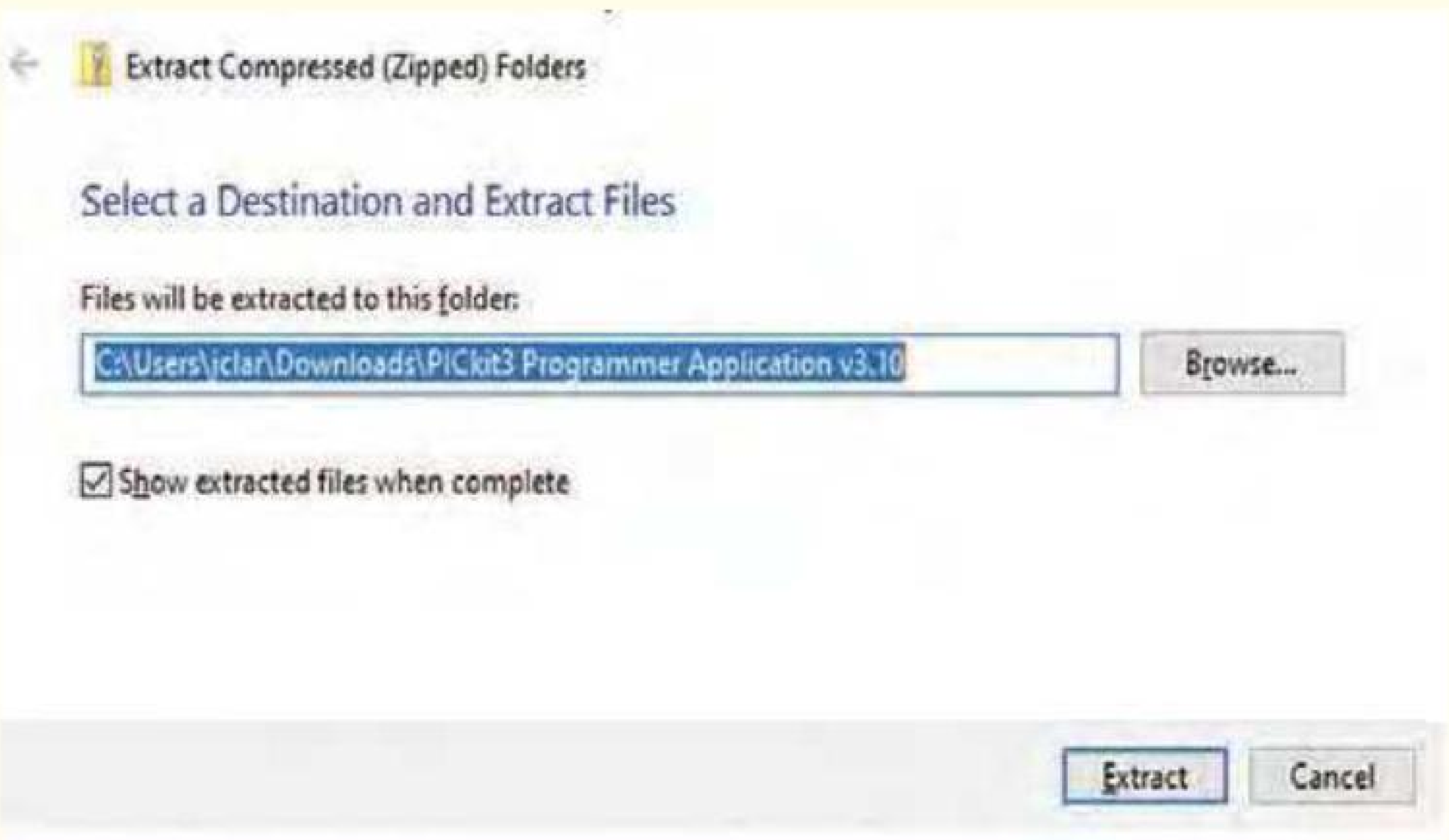
Screen23: after SpinASM itself is installed, the driver installer will launch. Click Next to complete the setup.

Installing the PICkit 3 Programmer software

The software zip file (the link is under 'PICkit 2 programmer emulator' in the main body of this article) is in a compressed format, often described as an 'archive'.

Open the file and select 'extract all', accepting the default folder (C:\Users\<username>\Downloads\PICkit3 Programmer Application v3.10), as shown in Screen24.

You can change the default extraction path if you like; it doesn't matter since, once installation is complete, you can delete the folder entirely.



Extract Compressed (Zipped) Folders

Select a Destination and Extract Files

Files will be extracted to this folder:

C:\Users\jclar\Downloads\PICkit3 Programmer Application v3.10

☑ Show extracted files when complete

Screen24: now that it has been installed, you can click Finish and launch the software.

With the box at the bottom ticked, the folder should appear as soon as the extraction process has finished. When that happens, launch the setup executable (normally done by double-clicking on the file). Use the default settings and file locations and agree to the conditions.

The installer will ask permission to install the software. Upon clicking 'Yes', the installation will begin. When completed, close the installer.

To save disk space and reduce clutter, after the installation has completed, you can delete the extracted installation folder, as the files will have been copied elsewhere on your system.

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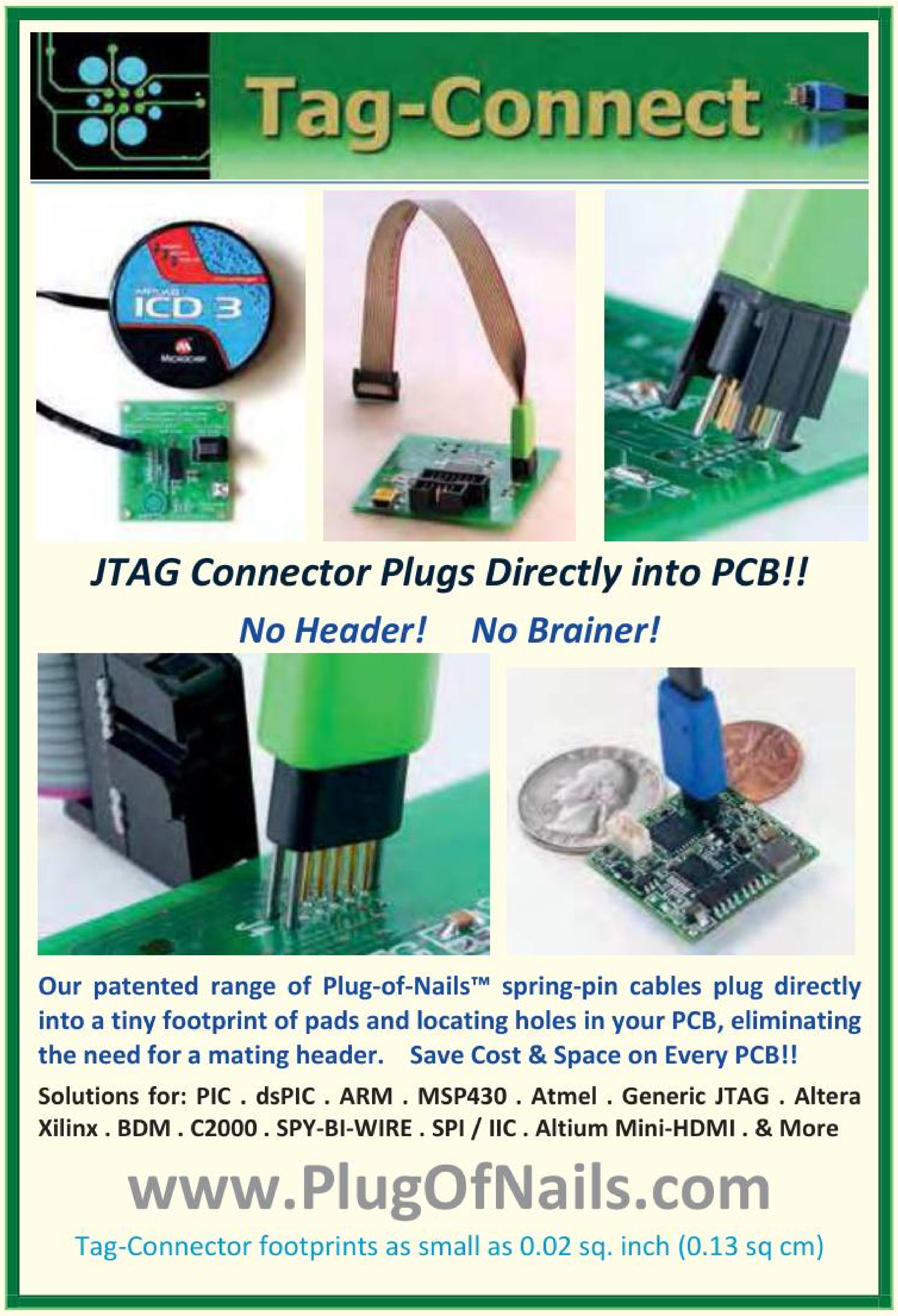

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Care for your rechargeable batteries

High-current Battery Balancer

Part 2 – by Duraid Madina

Introduced last month, our new *High-current Battery Balancer* is an advanced design which provides high efficiency and fast balancing by efficiently transferring charge between connected cells or batteries. It can handle cells or batteries up to 16V, and two units can be combined for larger installations. This second and final article describes the assembly and testing steps, and how to use it.

We put considerable effort into keeping this design as simple as possible, while still providing excellent performance and many useful features.

As a result, the parts count is not especially high. However, we have had to use mostly SMD parts to keep the size reasonable, and also because many of the best part choices were not available in through-hole packages at all.

Therefore, while the board assembly is not overly difficult, it is not suitable for beginners – some SMD soldering experience is desirable.

You will need a decent temperature-controlled soldering station (and ideally, a reflow oven or hot air rework station), a syringe of flux paste, some solder wick, fine-tipped tweezers, a magnifier and a strong light source.

None of the SMD parts are especially difficult to handle, although the smaller six-pin parts in SOT-363 packages are on the tricker side, along with QSOP-16 ICs, which have pins that are fairly close together. Finally, the transformers can present a bit of a challenge in making good solder joints due to their high thermal mass. But with a little care, the PCB can be built by hand.

Construction

The *High-current Battery Balancer* is built on a four-layer PCB coded 14102211 which measures 108 x 80mm. Refer to the PCB overlay diagrams, Figs.4(a) and 4(b) overleaf, for details on which parts go where. We suggest you start construction by populating the surface-mount components on the board's underside, followed by the SMDs on the top side, and then finally, the through-hole parts.

As touched on earlier, you can use various assembly methods, including reflow soldering or hand-soldering. We will describe the hand-soldering method as it requires the fewest specialised tools, as listed above.

The general procedure is to place each part (with the correct orientation for polarised parts, which is pretty much all ICs, diodes and MOSFETs) and tack down one pin. You then check the alignment of the other pins and re-position the part by melting the tack solder and gently nudging the part if it is not perfectly aligned with its pads. Once aligned, it is a good idea to add flux paste to all the pins, as that greatly reduces the chance of solder not adhering.

You then solder the remaining pins, refresh the initially tacked pin (if you have added flux paste then all you need to do is touch it with the tip of the iron), then use solder wick and flux to clean up any bridges which might have formed.

The order in which components are placed is not critical, but it's best to place the most difficult parts on each side first, so that you do not have to deal with interfering adjacent components. The following procedure uses that method.

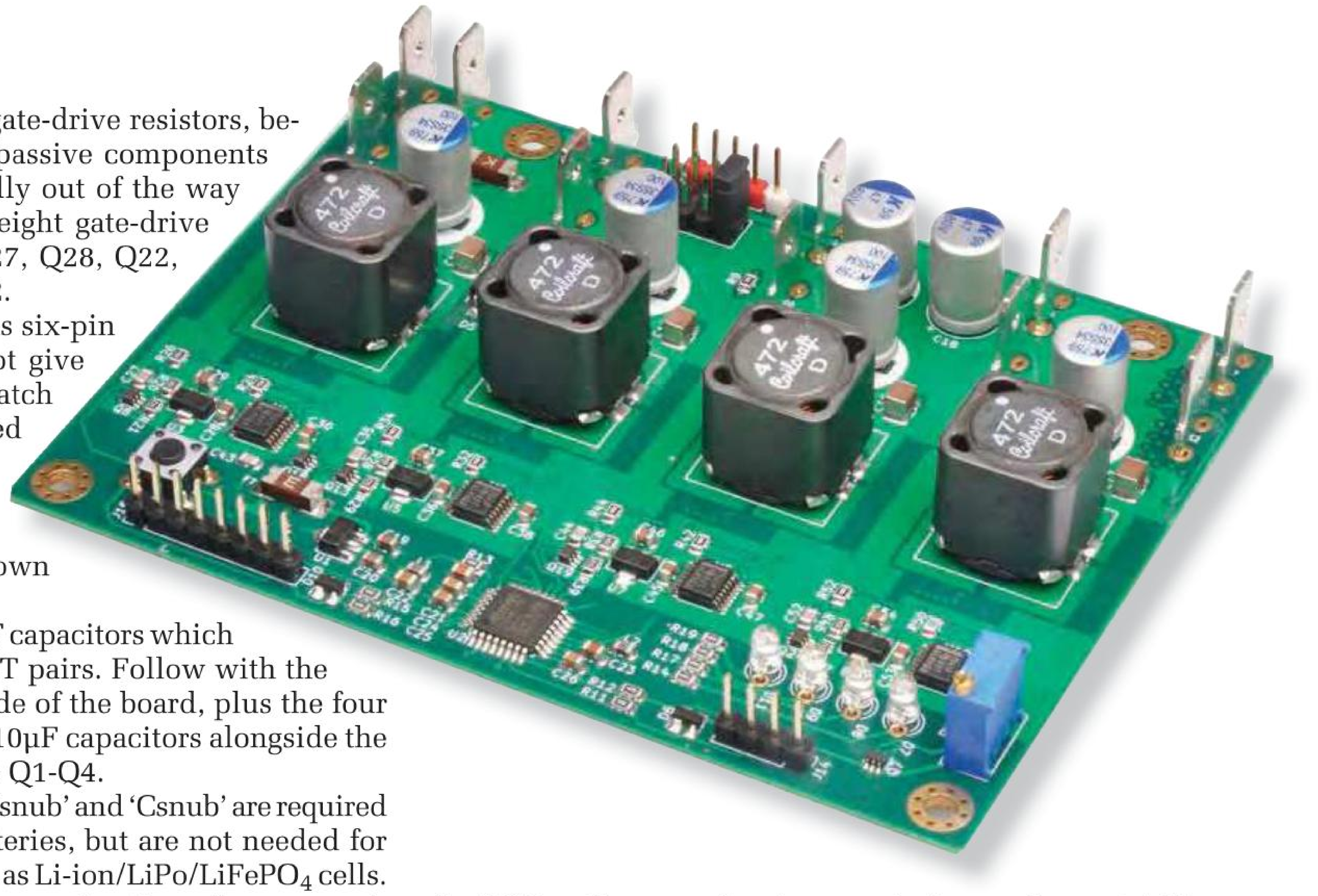
Note that SMD resistors are typically marked with a tiny code on the top that indicates the value (eg, 47kΩ = 473 [47 x 10^3] or 4702 [470 x 10^2]), which you probably need a magnifier to see. SMD ceramic capacitors are usually unmarked.

Finally, note that most of the semiconductor devices used are sensitive to electrostatic discharge (ESD) – particularly those in the smaller packages. Therefore, when handling these devices, try and avoid touching their pins. A grounded anti-static wrist strap will usually ensure you can't damage any parts, but there are many other ways of ensuring ESD safety.

Assembly details

Start by fitting the eight 1Ω gate-drive resistors, because they are the smallest passive components on the board and are generally out of the way of other parts. Next, fit the eight gate-drive NMOS/PMOS FET pairs: Q27, Q28, Q22, Q23, Q16, Q17, Q11 and Q12.

These are relatively large as six-pin SMDs go, so they should not give you too much trouble, but watch the orientation! You might need a magnifier to find the pin 1 dot on the top of each device, which in each case goes in the bottom right corner, as shown in Figs.4(a) and 4(b).



Next, mount the eight 4.7µF capacitors which are adjacent to these MOSFET pairs. Follow with the five 330Ω resistors on this side of the board, plus the four 20Ω resistors, then the eight 10µF capacitors alongside the mounting pads for MOSFETs Q1-Q4.

The components labelled 'Rsnub' and 'Csnub' are required if you are balancing 12V batteries, but are not needed for lower voltage balancing, such as Li-ion/LiPo/LiFePO$_4$ cells. If you need them, fit them now, using the values suggested in the parts list published last month (30Ω and 470pF).

Now install MOSFETs Q1-Q5. These are in LFPAK56 SMD packages, which are similar to 8-pin SOIC devices, but with a tab replacing four of the pins on one side. As such, it should be obvious which way round they go, but don't get the BUK9Y8R5-80E used for Q5 mixed up with the similar BUK9Y4R8-60Es used for Q1-Q4.

In each case, spread a little flux paste on the tab pad before tacking one of the small pins, then solder the remaining three small pins before the tab. You might need to crank your iron temperature up to solder the tabs as they have a lot of thermal mass. The flux paste you added earlier should help draw the solder you feed in under the tab for a good thermal and electrical connection.

With those in place, fit the eight remaining MOSFETs on this side of the board using the same technique. They are all BUK9Y14-80Es (a different type again from Q1-Q4 and Q5).

Now fit the four SMB TVS diodes, ZD1-ZD4, ensuring that their cathode strips are oriented as shown in Fig.4. Note that the voltage rating of these parts varies depending on what type of cells or batteries you are balancing (see the parts list last month).

Solder them similarly to the passives, but being larger, they take a bit more heat. Their leads wrap around the sides, so make sure the solder adheres to both the PCB and the device leads (flux paste makes this much easier to achieve).

The next job is to solder the four 3A SMD fuses, which mount similarly to resistors (they are not polarised). That just leaves two small resistors: one 100kΩ 0.1% resistor, and another 0.1% resistor, the value of which varies depending on your application. Make sure you don't get them mixed up.

Top-side SMDs

Flip the board over and continue assembly by fitting the four larger, 3.2 x 2.6mm (M3226 or 1210) sized ceramic capacitors near the transformer T1-T4 footprints. We used 4.7µF 100V capacitors (TDK CNA6P1X7R2A475K250AE) but you can more than double the capacitance by using 10µF 75V capacitors which cost only a little bit more (TDK CGA6P1X7R1N106K250AC).

Follow by fitting the five small dual MOSFETs, Q8, Q18, Q13, Q19 and Q24. In each case, make sure that the pin 1 dot is lined up correctly first. These are in smaller packages than the ones you mounted on the bottom of the PCB, with more closely spaced pins, so they might be a little bit trickier. But they aren't too hard as long as you remember to carefully check for bridges between pins using a magnifier and fix any bridges you find using flux paste and solder wick.

MOSFET Q7, in the bottom-right corner, is in the same package as those five but it is a slightly different device, so don't get it mixed up. Again, check its orientation carefully before soldering it in place.

Now is a good time to mount the microcontroller, IC2. It should be relatively easy compared to the devices you have already soldered, but make sure that the pins on all four sides are lined up before soldering more than one pin, and as usual, be careful to get its pin 1 in the correct location.

Follow with the four isolators: IC4, IC6, IC8 and IC10. In each case, pin 1 is at upper left. These have a similar pin pitch to the small dual MOSFETs you already mounted, so should not be any harder to install.

Next, fit the eight 470nF capacitors, followed by the five regulators. For the regulators, spread a little flux paste on the large pad before tacking one of the smaller pins, then solder the remaining small pins before tacking the tabs.

You might need to turn your iron temperature up a bit when soldering the tabs.

With those in place, now you can fit the six 1µF SMD capacitors, the two ferrite beads, plus the 680Ω and 100Ω SMD resistors. Then mount the two ESD protection arrays, which are in four-pin packages with one larger than the others. Check Fig.4(a) and to verify their orientation if you are not sure.

Now install the eight 10kΩ resistors and then the five 1nF, three 100nF and three 10µF capacitors. Follow by fitting the remaining TVS (the higher voltage one, ZD5). Make sure it is oriented correctly. Then mount the two fuses, with the lower-current (0.75A) fuse being F7, near 8-pin header CON15, and the higher-current (3A) fuse near CON2 at upper left.

In terms of passives, that just leaves the sole 20Ω resistor near CON10, plus the eight 0.1% resistors.

As we mentioned last month, the lower value 0.1% resistor values need to be changed depending on your battery voltages.

The upper resistor in each pair is 100kΩ. Ensure that the lower resistor is either 6.8kΩ, for a total stack up to about 24V, or 2.2kΩ for higher stack voltages.

Transformer mounting

Due to the significant thermal mass of the transformers and the large power planes they connect to, we recommend avoiding the use of solder paste for mounting these parts, unless you have a very high-quality reflow oven.

Instead, we suggest placing them as accurately as possible, holding them in place with Kapton tape, then soldering their four tabs with a hot iron and flux-cored wire solder.

Once the transformers are fitted, it is essential to ensure that all flux residues are removed. This can be challenging as most residues will be hidden between the underside of the transformers and the PCB.

If flux residues are allowed to remain, the idle current can increase by orders of magnitude (beyond 1mA). The flux can break down at higher voltages, resulting in erratic behaviour and even arcing through the residues.

Here, an ounce of prevention is worth a pound of cure, so try to limit the build-up of flux residue by not allowing too much to accumulate in the first place. If you have the choice, try to use a 'no-clean' flux. However, if the flux you are using requires cleaning, make sure to wash the transformers thoroughly with a high-quality flux remover and wipe off any visible residue.

Through-hole components

Fit tactile switch S1 now. It has a standard footprint, so switches with various actuator heights are available. If you will be frequently adjusting the unit, you might consider chassis-mounting a switch and wiring it back to the pads. If doing that, make sure the wires connect to one of the upper pair and one of the lower pair (which is GND).

Then you can fit terminal blades for battery/cell connection as required. Most 5.08mm-pitch two-terminal types will work, but check to make sure your intended spade connector will fit.

An example blade is Wurth Elektronik 7471286, or use the Altronics parts suggested in the parts list last month.

It may be preferable to solder wires instead of spade lugs for some installations, perhaps to reach panel-mounted connectors.

However, the *Balancer* should not be directly soldered to batteries. A failure in either the *Balancer* or the batteries will be more difficult to resolve if the two are permanently connected.

There is no need to use particularly heavy gauge wire, as balancing currents are modest, but as a rough guide, they should be able to carry 2A with a negligible temperature rise. 0.8mm-diameter copper wire (20AWG) is a reasonable option.

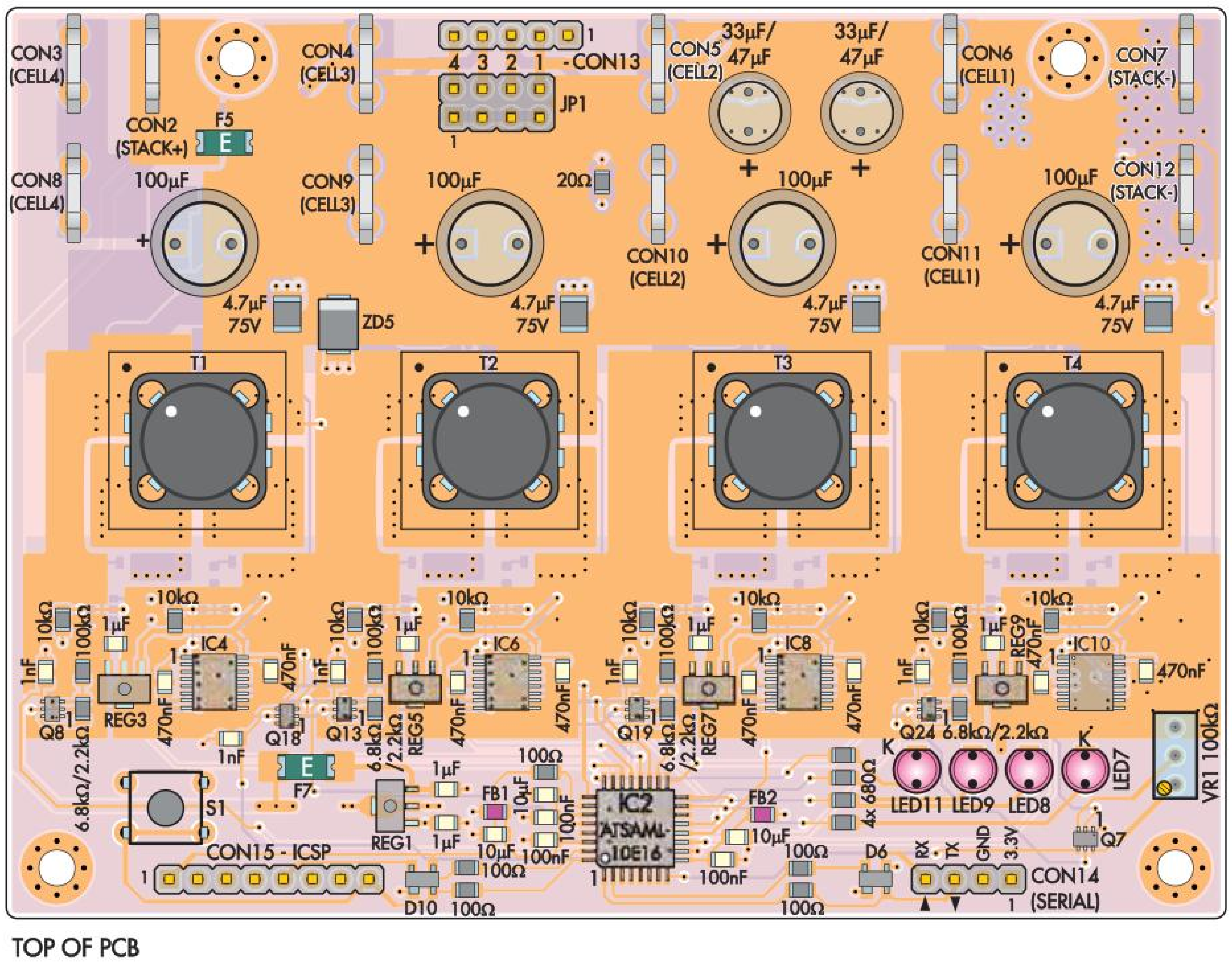
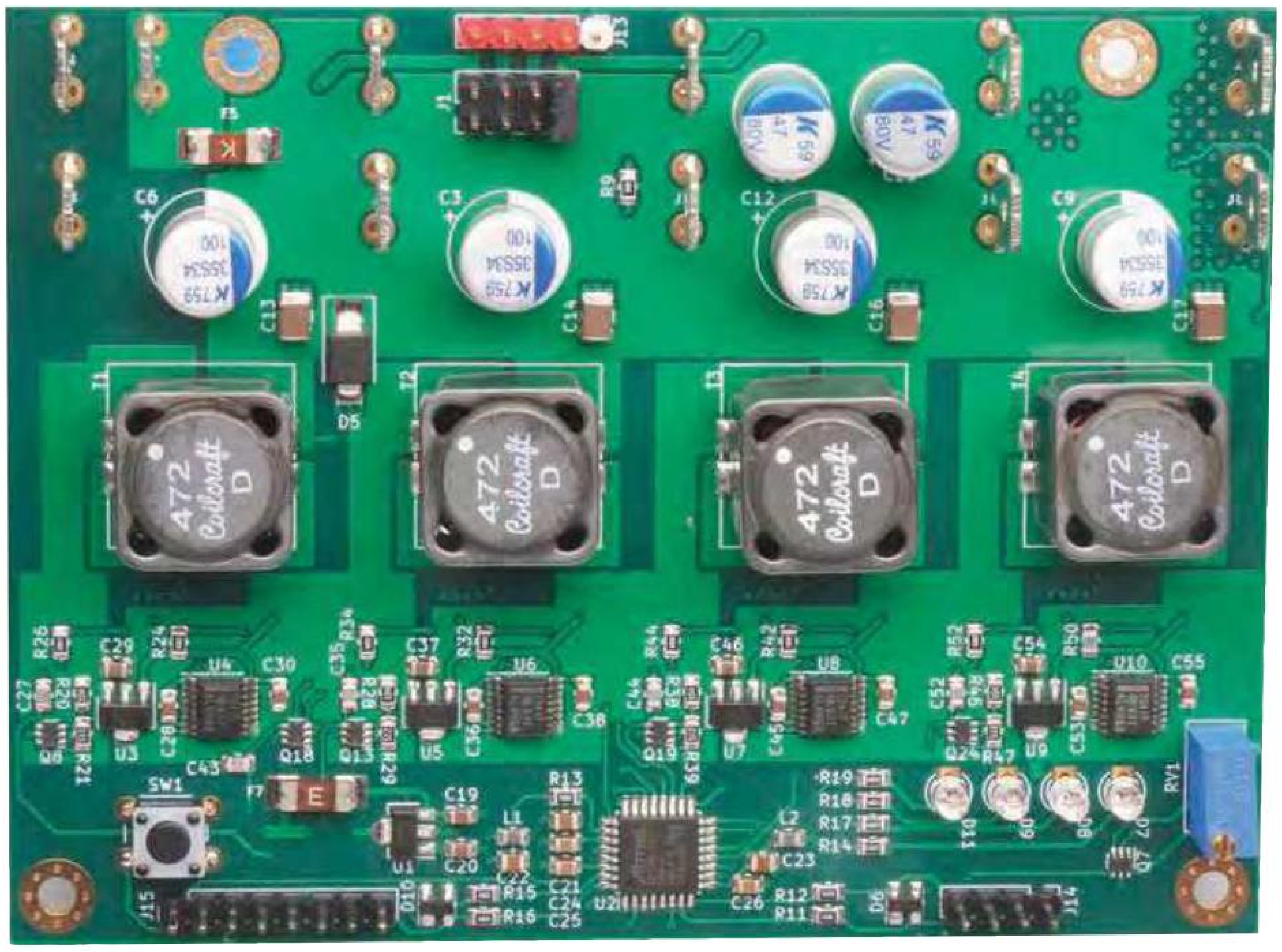

CON3 (CELL4)
CON4 (CELL3)
4 3 2 1 CON13
JP1
CON5 (CELL2)
33µF/ 47µF
33µF/ 47µF
CON6 (CELL1)
CON7 (STACK-)
CON2 (STACK+)
F5
CON8 (CELL4)
100µF
CON9 (CELL3)
100µF
20Ω
100µF
100µF
CON12 (STACK-)
CON10 (CELL2)
CON11 (CELL1)
4.7µF 75V
ZD5
T1
T2
T3
T4
10kΩ
1µF
100kΩ
1nF
470nF
IC4
IC6
IC8
IC10
REG3
REG5
REG7
REG9
Q8
Q13
Q18
Q19
Q24
6.8kΩ/2.2kΩ
S1
F7
FB1
FB2
IC2 ATSAML10E16
REG1
100Ω
10µF
100nF
4x 680Ω
LED11 LED9 LED8 LED7
VR1 100kΩ
Q7
D6
D10
CON15 - ICSP
RX TX GND 3.3V
CON14 (SERIAL)
TOP OF PCB

Fig.4(a): top-side PCB component overlay, with matching photo below.



If you are using spade lugs, then ensure that no part of the blade, lug or wire can contact other nearby components. Insulated spade quick connectors are available, and it's a good idea to use them.

For some installations, you might want to mount the board inverted and have terminals or wires exiting from the rear of the board.

You can also fit a 5-position 2.54mm header (either vertical or right angle) at CON13 for lower-power applications such as balancing smaller lithium-polymer (LiPo) batteries.

CON13 is conveniently located at the edge of the board. If the board is mounted right at the edge of a case with a cut-out in the side, you can plug a standard balance connector straight in. However, you do need to be careful with the polarity!

Now is a good time to fit the 2x4-pin header for JP1. For some installations, where the batteries are of a fixed type, this could be replaced with a soldered wire link. Follow with trimpot VR1, ensuring its adjustment screw is located as shown.

If you will be adjusting the balancing voltage frequently, you could instead use a chassis-mount 100kΩ potentiometer and run flying leads back to VR1's pads, possibly plugging into a pin header.

Neither the potentiometer's accuracy nor power dissipation are critical, but we suggest using a sealed design for greater long-term reliability.

Follow with the four LEDs, ensuring that the cathodes face towards the top as shown. If mounting the LEDs on the PCB, you will need to use 3mm types.

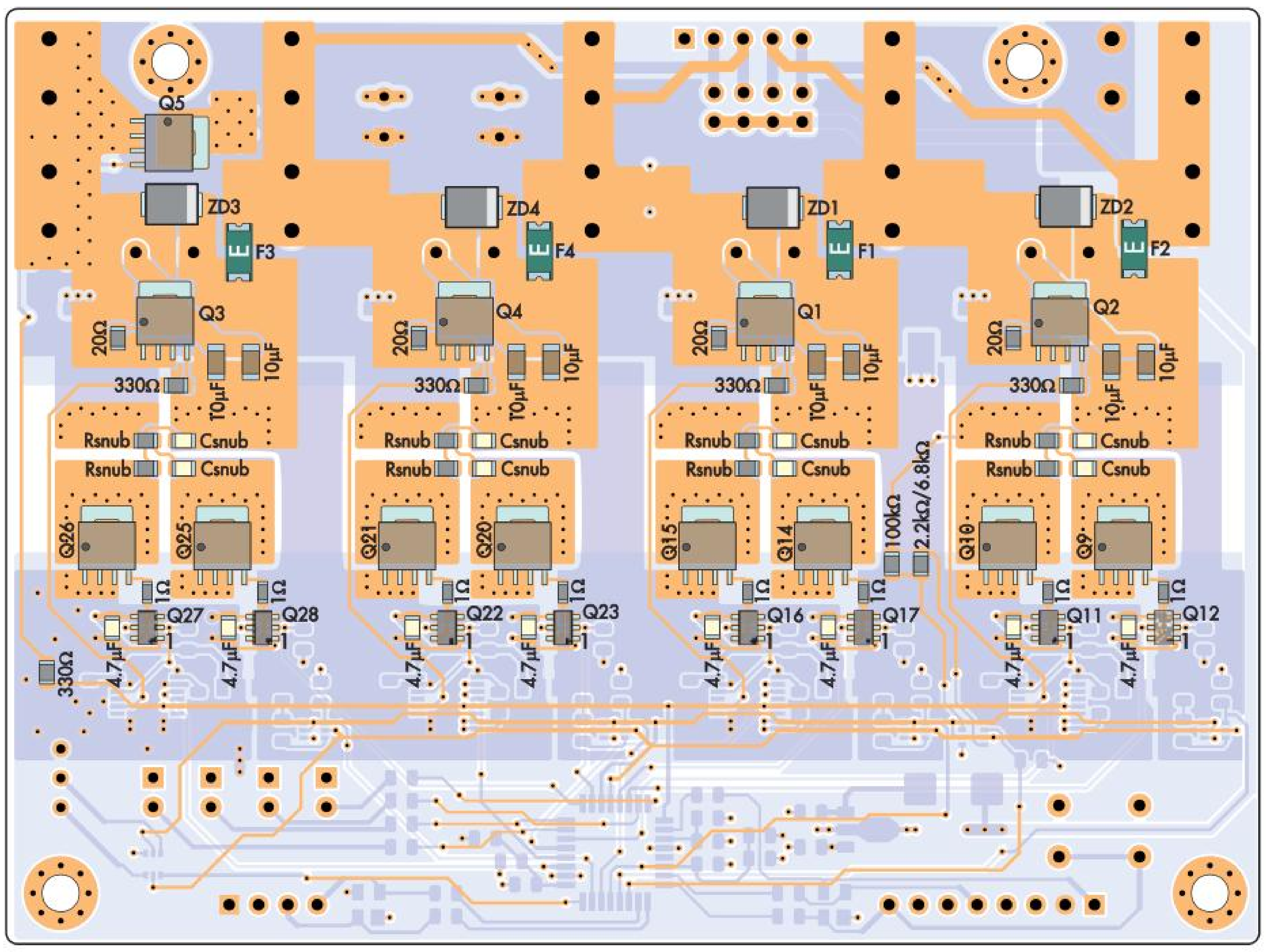
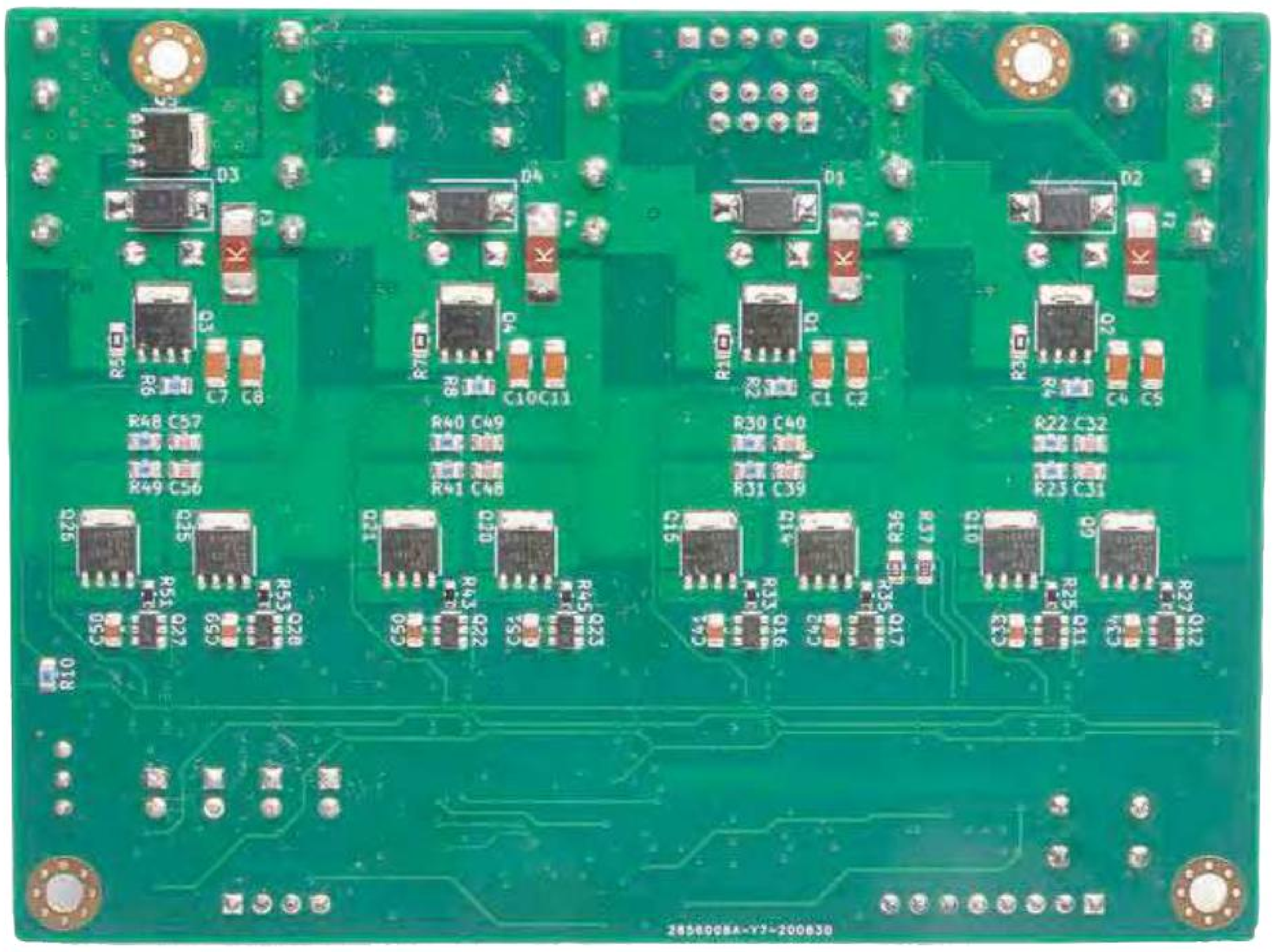


Fig.4(b): and here's the underside of the board, again with matching photo below.



Alternatively, you could instead fit pin headers or flying leads and mount them in a location that will be externally visible (eg, mounted onto a panel or case side using bezels), in which case you could use 5mm LEDs or virtually any other types.

For some colours, a different value current-limiting resistor from the 680Ω specified could be used to raise brightness or lower power consumption.

As the drive voltage is 3.3V, blue or white LEDs are not recommended, although you might find that such types give adequate light given their high efficiency.

Pin headers CON14 and CON15 are optional. CON14 is only required if you need access to the serial port, such as for debugging or connecting two *Balancers* to work together (via an isolator) on an 8-cell battery.

CON15 is only needed if you have fitted a blank microcontroller and will need to program it on-board, or wish to reprogram it later.

That just leaves the six capacitors. Don't get the two different types mixed up, and make sure to insert the longer leads into the holes marked with '+' signs.

Note that we have specified organic polymer capacitors, not ordinary electrolytics, for their much superior performance characteristics.

Programming

When it comes to programming IC2, as mentioned last month, this can be done with a PICkit 4 plugged into CON15 (pin 1 to pin 1). This is best done using the MPLAB X IPE software, which comes with Microchip's free MPLAB X IDE.

It's very important not to program the device while attached to any kind of power source (cell/battery or otherwise), so enable the 'power target from PICkit' option.

Test the device in low power/current limited situations after programming, as described below, in case there's an error with the newly programmed software.

Testing

Before connecting the *Balancer* to batteries, it's essential to test it to ensure that nothing has gone wrong with the assembly that could affect the circuit's safety or reliability.

The easiest way to do this is with a pair of isolated, current-limited power supplies. Set their output voltages to be the same (eg, 4V each) and their current limits to around 500mA.

Connect one supply between STACK– (CON7) and CELL1 (CON6), with the positive terminal to CON6. Connect the other between CELL1 (CON6) and CELL2 (CON5), with the positive terminal to CON5.

Ensure that a jumper is installed so that the control block is powered from one of these two points, ie, at the positions marked 1 or 2 for JP1 (across pins 1 and 2, or pins 3 and 4).

With an oscilloscope, check to see periodic pulses on the SENSE_EN and SAMPLE lines (pins 19 and 20 of IC2 respectively). If these are absent, there is a fault in or around the microcontroller, or it is not receiving power.

If you don't have a scope, you might be able to pick up the pulses using the frequency counter mode on a DMM, or even an analogue voltmeter.

If the microcontroller is functional, tie the top-most cell to the stack voltage rail (connecting CON5 [CELL2] to CON2 [STACK+]), and slowly make a small change to the voltage of one of the cells.

You should see that the voltage on the power supply with the lower output voltage increases.

If this is difficult to observe, then you can try using an oscilloscope to check the CSPWM/SSPWM lines on the corresponding cell (pins 11 and 17 for the lowest cell or pins 12 and 18 for the second-lowest). You should see narrow, square pulses on these lines.

If this test is successful, check the third and fourth cell sections, but note that cells must always be populated in-order from ground; none can be left empty except at the top.

If you are considering higher-voltage applications, test these carefully, taking great care to use appropriate current limits, and ensuring that the

Safety notes

Working with batteries presents some hazards. The most important thing to do is to be thoroughly familiar with your particular batteries' safety requirements. In general, having fuses close to the terminals of all larger batteries is a good idea to prevent cables catching fire.

You can buy fuses that connect directly to the terminals, with provision to attach thick wires at the other end. You can also use inline fuses, but you should ideally keep the section of wire between the terminal and fuse short.

There are a few other things to keep in mind when using the **Balancer**:

- Always check that the **Balancer** is working as intended before attaching it to batteries or other power sources. Ideally, this is done with current-limited power supplies, as described in the main text.
- Don't leave the **Balancer** unattended until you are satisfied that it works reliably for your particular application. Take particular care if setting a lengthy timeout period.
- Keep the **Balancer** physically separate from the batteries. If they are too close, heat from the **Balancer** could degrade the batteries, or lead to a hazardous situation.
- Ensure that the **Balancer** is kept clean and dry at all times.
- Don't permanently attach the **Balancer** to batteries or other power sources; if a hazardous situation arises, it is good to have the ability to quickly disconnect the **Balancer**.
- Periodically check that your batteries are healthy: if the **Balancer** is constantly balancing one cell, or if you notice that your batteries are losing their ability to store charge, be sure to test and replace any failing cells.
- Remember that the **Balancer** can't stop a battery from being charged or discharged by external circuitry: over-charging and over-discharging cells can not only damage them, but can lead to hazardous situations.
- Note that in higher voltage applications, some of the voltages present on the **Balancer** could be dangerous (although its maximum rating of 60V total is well within the extra-low-voltage or ELV domain) and so the **Balancer** should not be touched. Additionally, some components on the **Balancer** can get hot during operation.

control logic section is powered from only the lowest possible cell.

This avoids wasted power in the control regulator (REG1) and potential damage if its maximum input voltage is exceeded.

In general, if your lowest expected cell or battery voltage is above 3.6V, then you should always leave JP1 in position 1, so the control circuitry runs off the lowest cell.

If your lowest expected cell voltage is lower than this, down to the minimum supported of 2.5V, then it should always be safe to run the control circuitry off the second cell (position 2 on JP1).

Higher positions are only useful if you need to ensure that the small current which powers the control section comes from the whole stack, which would be unusual.

Final assembly

Once you have finished testing your *High-current Battery Balancer* board, it should be enclosed to protect it from dust and any other contaminants.

You can use just about any housing or box that's large enough to accomodate the PCB module, and which allows cables to be fed through. Ideally, it should offer some method of exposing the LEDs (eg, a clear lid), potentiometer and pushbutton (possibly via a screwdriver through small holes in the lid).

Mount the PCB to the bottom of the case using standoffs so that the board does not flex, and take care that all of the components have adequate clearance from the case walls as it can dissipate some heat.

Four mounting holes are provided to suit M3 machine screws, and plastic or metal spacers can be used. Just be careful if using metal spacers that they fit within the copper areas provided around the holes.

Heatsinking is not usually required on any of the components, but allowing even a modest amount of airflow will go a long way towards keeping the *Balancer* cool, prolonging its life.

In harsh environments, a small temperature-switched fan could be used (eg, with the thermal switch glued to transformer T1).

However, in most cases, passive airflow will be adequate – just a few vents or holes drilled in the bottom and the top, or the sides of the case, being sufficient for convection to remove the heat.

Using it

Now that you've built and tested your *Balancer*, how do you use it? Before connecting it to a battery, run through the following checklist to make sure it's correctly configured:

1) Configure the source of control power. As described above, if balancing 12V batteries, ensure that the control power source select jumper is securely installed in the right-most position (marked 1), so that the lowest cell is providing control power.

If balancing a ~3.6V cell (eg, Li-ion, LiPo or $LiFePO_4$), you will probably want the power source select jumper in the second-rightmost position, so that the lowest pair of cells are providing control power.

2) Connect the battery leads to their respective terminals. We suggest connecting them either sequentially (CELL1, CELL2…) or simultaneously (if using an external connector).

Plug spade quick connects onto CON8-CON12 for higher-current applications, or a plug designed to mate with 2.54mm-pitch header pins to CON13 for balancing up to 1A.

If using CON13, make sure the plug orientation is correct, with the negative-most terminal to pin 1! There might be small sparks when connecting battery leads, but these should be momentary.

3) Finally, connect the stack leads (STACK– to CON7 and STACK+ to CON2). If balancing, you can simply bridge the positive stack voltage terminal to the top-most cell terminal.

For charging, connect the negative stack terminal to the negative end of your power source, and the positive stack terminal to the positive end.If available, we recommend setting a reasonably low current limit on your power source, to help prevent damage to batteries in case of malfunction.

Making adjustments

Operation is essentially automatic, with the *Balancer* simply transferring charge based on the differences it senses in voltage across the batteries or cells. However, there are some options you can set, either using trimpot VR1 and pushbutton S1, or via the serial interface.

The options include the minimum difference between battery/cell voltages for balancing to start, the maximum balancing current and the minimum and maximum battery/cell voltages outside which balancing will cease.

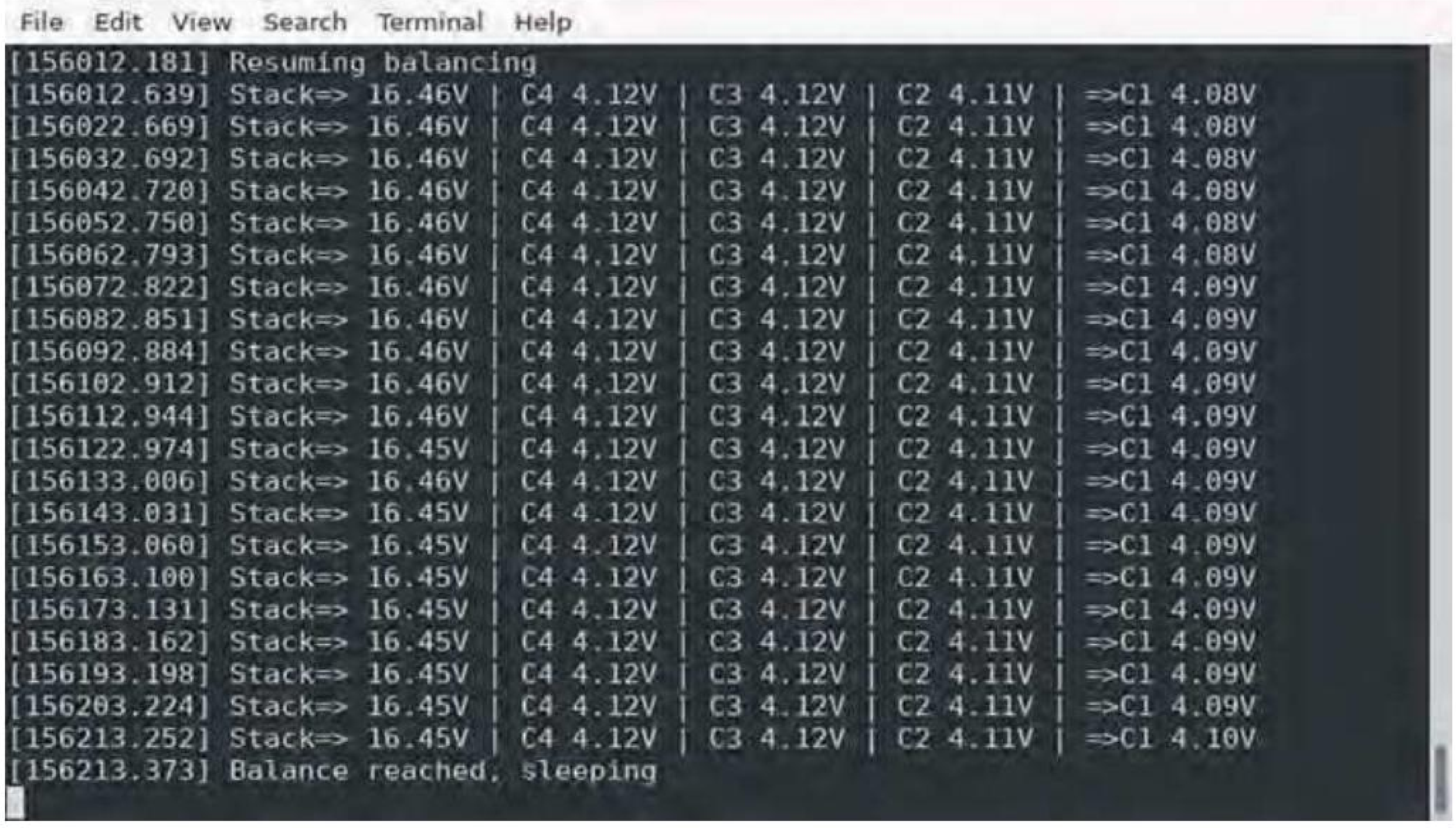
The defaults are for the maximum possible balancing current (about 2.5A), to begin balancing with a 50mV imbalance for 12V lead-acid batteries or a 10mV imbalance for Li-ion cells, and for an operating cell voltage range of 2.5-4.3V for Li-ion applications and 10-14.8V for nominally 12V batteries.

You can change most of these settings using trimpot VR1 and pushbutton S1, although a larger range of configuration and calibration settings are available via the serial/USB interface.

Table 1 shows the various commands which can be issued by pressing pushbutton S1 in various ways – either a single, long press or with several short presses in a row. Some of these control the unit while others adjust settings in combination with the current rotation of trimpot VR1.

Unfortunately, making settings changes this way is a bit imprecise. You can measure the voltage at the wiper of VR1, either by probing its centre pin on the bottom of the board with a DVM or by probing pin 3 of nearby MOSFET Q7 relative to GND. You then need to divide that reading by 1.65V (or better, the actual measured 1.65V ADC reference voltage) and then multiply by the range given in Table 1 below.

If you can hook up the serial interface, you are much better off making changes that way as they will be exact, and you can also calibrate the unit properly that way. Read on for further details on the serial interface.



```
[156012.181] Resuming balancing
[156012.639] Stack=> 16.46V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.08V
[156022.669] Stack=> 16.46V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.08V
[156032.692] Stack=> 16.46V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.08V
[156042.720] Stack=> 16.46V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.08V
[156052.750] Stack=> 16.46V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.08V
[156062.793] Stack=> 16.46V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.08V
[156072.822] Stack=> 16.46V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156082.851] Stack=> 16.46V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156092.884] Stack=> 16.46V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156102.912] Stack=> 16.46V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156112.944] Stack=> 16.46V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156122.974] Stack=> 16.45V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156133.006] Stack=> 16.46V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156143.031] Stack=> 16.45V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156153.060] Stack=> 16.45V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156163.100] Stack=> 16.45V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156173.131] Stack=> 16.45V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156183.162] Stack=> 16.45V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156193.198] Stack=> 16.45V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156203.224] Stack=> 16.45V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.09V
[156213.252] Stack=> 16.45V | C4 4.12V | C3 4.12V | C2 4.11V | =>C1 4.10V
[156213.373] Balance reached, sleeping
```

Screen1: sample serial output.

Monitoring its operation

The simplest way to do this is visually. One of the four LEDs on the board will flash to indicate when balancing is occurring, with the right-most LED (LED7) corresponding to the bottom-most cell, LED8 to the next cell up in the stack and so on.

They blink slowly if a battery/cell is being charged, or rapidly if a battery/cell is being discharged.

If no balancing/charging is occurring, LED7 will occasionally flicker very lightly, just to let you know that the circuit is 'alive', while consuming as little power as possible.

If there is an over-voltage error, all four LEDs will flash simultaneously at 1Hz, with a 50% duty cycle.

If an under-voltage error is detected, then the unit simply shuts down and does not flash the LEDs at all (not even a heartbeat).

If you are paying attention, the lack of heartbeat will tell you something is wrong, and by leaving the LEDs off, we don't risk discharging an already over-discharged cell or battery.

If you want more details of the unit's operation and be sure that it is doing its job, you can monitor the serial port at CON14. Ideally, this should be connected to your computer via an isolating interface (a good one is described below).

You can then wire the output of that isolating interface to a USB/serial adaptor.

Set a terminal emulator to 38,400 baud N,8,1 and you should see a stream of information, like that shown in Screen1. This shows you the measured voltage at each input, plus the whole stack, whether it is currently moving any charge into or out of a battery/cell, and how fast it is doing so (0-100%).

The data is both human-readable and machine-readable, so it would be quite easy to create software to parse the information and display it differently, or take actions depending on the results.

As shown in Table 2, you can also send commands to pause or resume balancing, change the settings, or even force it to transfer charge into or out of a given battery/cell. This means that you could centralise the control via a computer program if you are using several *Balancer* boards.

Combining multiple balancers

You can use two *Balancer* boards to balance up to eight batteries or cells, as long as the total stack voltage is still within the 60V DC maximum rating. The only extra hardware that you need to do this is an isolated serial link.

Fortunately, we published just such a design in March 2022 (see page 14 for the *Mini Isolated Serial Link* project). PCBs are available for this design from the *PE PCB Service*.

220Ω
CON1
1kΩ
100n
JP2
1kΩ
100n
JP1
CON2
220Ω

From Practical Electronics, March 2022: this Isolated Serial Link is ideal for connecting two Balancer boards together.

Function	Number of S1 presses
Check that unit is powered up	One short (<500ms)
Pause/resume balancing	One medium (1-2s)
Switch between Li-ion and lead-acid presets	One long (5s+)
Set allowable voltage delta (0-300mV/0-1V)	Two short
Set maximum balancing current (0-2.5A)	Three short
Set minimum battery/cell voltage (0-5/0-15V)	Four short
Set maximum battery/cell voltage (0-5/0-15V)	Five short

Table 1: functions accessible by pressing pushbutton S1

Example	Result
p	Pauses automatic balancing
r	Resumes automatic balancing
t 600	Set balancing timeout to 600s; if balance not reached in this time, shut down
l 3000	Set low battery/cell threshold to 3V (3000mV); below this, it shuts down
h 4300	Set high battery/cell threshold to 4.3V (4300mV); above this, it shuts down
d 50	Batteries/cells can vary by up to 50mV before balancing starts
i2 50	Move charge into battery/cell #2 (1-4) at 50% of maximum rate (1-100)
o3 25	Move charge out of battery/cell #3 (1-4) at 25% of maximum rate (1-100)
c2 100000 6790	Calibration – set battery/cell divider #2 to have a voltage division ratio of 100kΩ:6.79kΩ
st 100000 6812	Calibration – set stack divider to have a voltage division ratio of 100kΩ:6.812kΩ
v 3280	Calibrate – set the typical supply voltage to 3.28V (3280mV)

Table 2: Serial commands

Build that board, but leave off the headers, and set both jumpers (JP1 and JP2) to the 5V position (they will actually be supplied with 3.3V, as that is the only low-voltage rail available on the *Balancer* boards).

You can then solder pins 3-6 of either CON1 or CON2 directly to CON14 on one of the *Battery Balancer* boards, as the pinout is an exact match.

Run a ribbon cable or similar from the other end of the board to CON14 on the other *Balancer* board. The wiring will be the same as the other end and you should have the TX pin on the *Balancer* connected to the TX pin on the *Isolator* board.

Similarly, the RX pin on the *Balancer* connects to the RX pin on *Isolator*. The reversal is effected within the *Isolator*.

Then, all you have to do is connect between one and four contiguous cells/batteries in your stack to one *Balancer* board, starting with the CELL1 connection, and join the remainder to the other.

Connect both full stacks across the STACK– and STACK+ terminals on both boards.

The two units will power up and negotiate over the serial link, automatically detecting that they are talking to each other.

They will then balance as if they are one eight-input *Balancer* instead of two four-input *Balancers*.

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This CD-ROM version of the exciting and popular *Teach-In 8* series has been designed for electronics enthusiasts who want to get to grips with the inexpensive, immensely popular Arduino microcontroller, as well as coding enthusiasts who want to explore hardware and interfacing. *Teach-In 8* provides a one-stop source of ideas and practical information.

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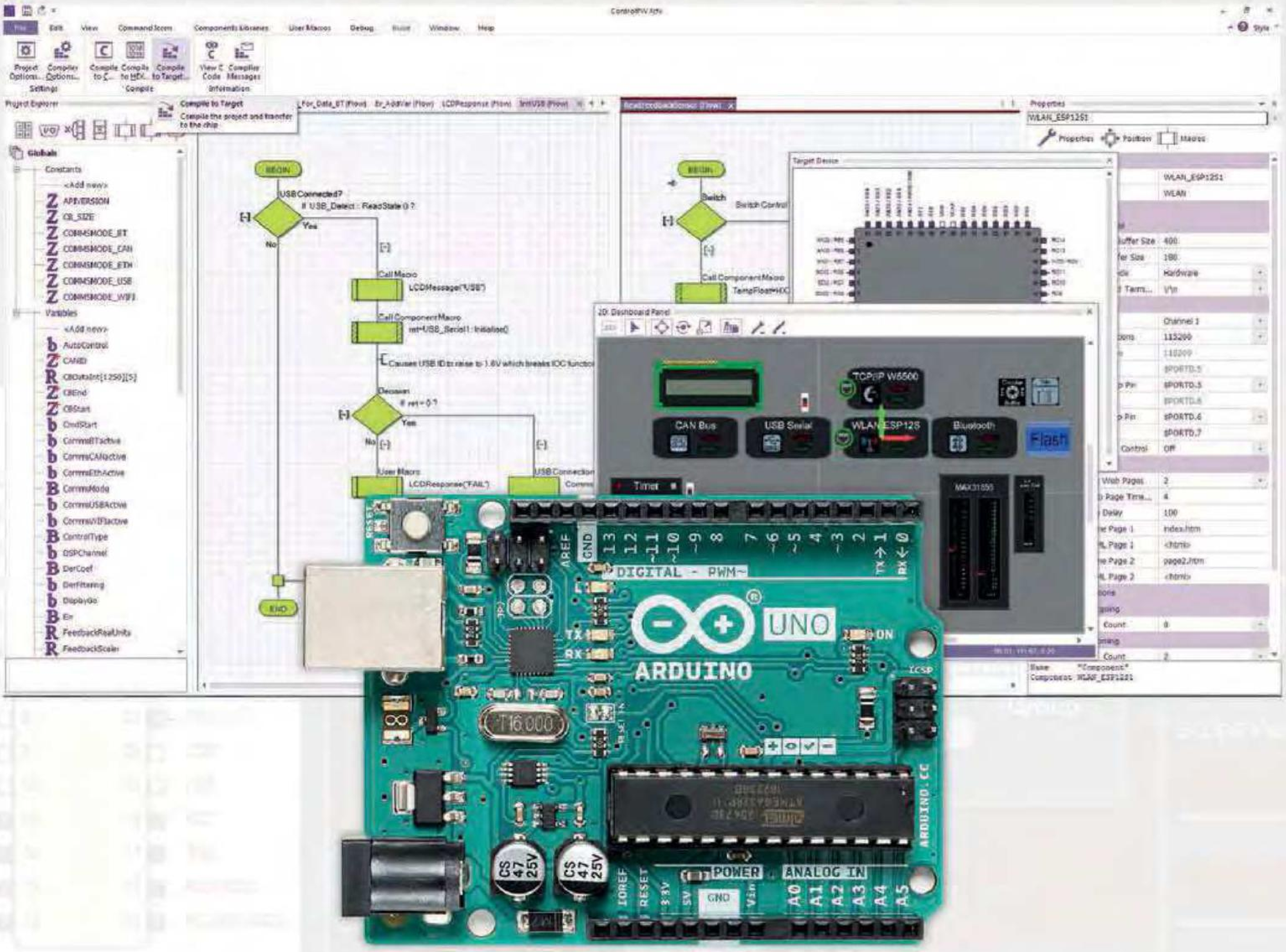
BEGIN
USB Connected?
Call Macro
Call Component Macro
Decision
END
2D: Dashboard Panel
CAN Bus
USB Serial
TCP/IP W5500
WLAN_ESP12S
Bluetooth
Flash
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KickStart

by Mike Tooley

Part 8: Introducing the Raspberry Pi Pico

Our occasional *KickStart* series aims to show readers how to use readily available low-cost components and devices to solve a wide range of common problems in the shortest possible time. Each of the examples and projects can be completed in no more than a couple of hours using 'off-the-shelf' parts. As well as briefly explaining the underlying principles and technology used, the series will provide you with a variety of representative solutions and examples, along with just enough information to be able to adapt and extend them for your own use.

This eighth instalment provides you with an introduction to the popular Raspberry Pi Pico microcontroller. We'll describe its architecture and how to make a simple application. So, if you've not dabbled with microcontrollers before, the compact Pico could be just what you've been waiting for!

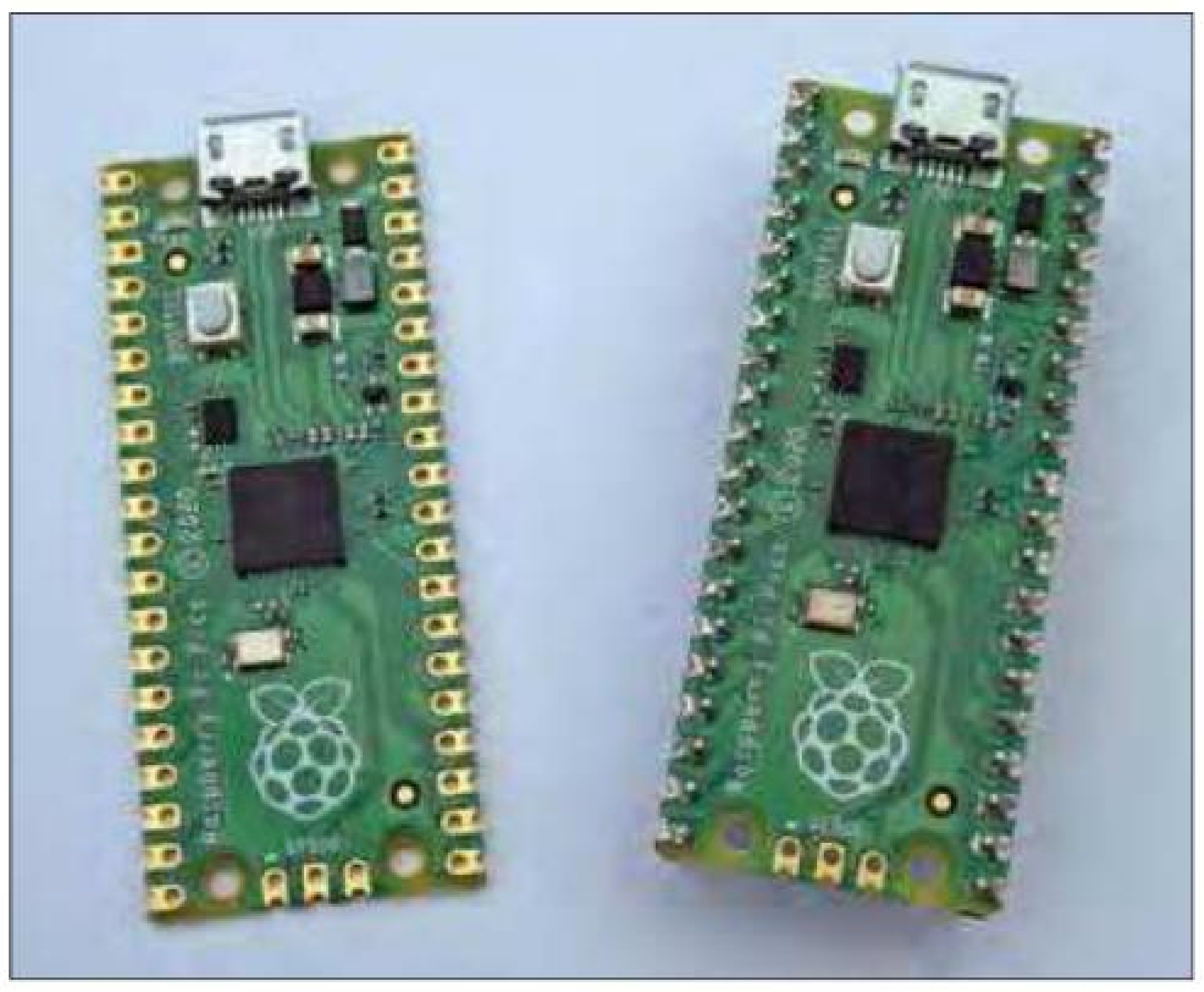


Fig.8.1. Versions of the Raspberry Pi Pico are available with and without headers.

The Raspberry Pi Pico microcontroller builds on the success of more than a decade of Raspberry Pi (RPi) computers. At the outset, it's important to be aware that this new board isn't a cut-down version of its big brother. Instead, it's perhaps best to think of it as a low-cost general-purpose microcontroller with RPi pedigree, but without all the bells and whistles of a full-blown RPi computer. For example, there's no Ethernet connection, no monitor port and no camera interface. However, what you do get is a competent and very soundly engineered microcontroller that not only delivers comparable functionality to that of the immensely popular Arduino Uno and Nano boards, but also has a few added features that can help to make life easy. Key features of the RPi Pico include:

- Dual-core ARM Cortex-M0+ processor
- Flexible clock running at up to 133MHz
- 264kB of SRAM, and 2MB of on-board Flash storage
- 26 multi-function GPIO pins
- Three 12-bit ADC channels
- 16 controllable PWM channels
- Two SPI, two I^{2}C and two UART for communication
- Accurate on-chip clock and timer
- Processor temperature sensor
- Eight programmable I/O state machines for custom peripherals
- Fast floating-point libraries in ROM
- USB 1.1 programming connection
- Low-power sleep and dormant modes.

When assessing the suitability of a microcontroller for use in a particular application it can be useful to compare it with existing devices. For example, Table 8.1 provides a comparison of the RPi Pico and the popular Arduino Nano.

What's on the board?

The RPi Pico is supplied on a printed circuit board that measures a miniscule 51 × 21mm (slightly larger than an Arduino Nano but significantly smaller than an Arduino Uno). The board is supplied in two versions; one without

Table 8.1. Comparing the Raspberry Pi Pico and Arduino Nano

Feature	Raspberry Pi Pico	Arduino Nano*
Microcontroller	RP2040	ATmega328
RAM	264kB	2kB
EAPROM	2MB	32kB (2kB bootloader)
Clock speed	Up to 133MHz	16MHz
USB interface	Micro. USB	Mini. USB
Communication	I^{2}C (2), SPI (2), UART (2)	I^{2}C, SPI, UART
ADC	3 × 12-bit	8 × 10-bit
PWM/DAC channels	Up to 16	6
Digital I/O	23 digital I/O lines with three available for ADC	14 digital I/O lines
Debug port	Yes (via three-pin SWD connector)	No
Supply	5V regulated or 1.8V to 5.5V (typically using a 3.7V LiPo battery – see text)	5V regulated, or 7V to 12V regulated
Pins	40 pins (DIL compatible) and 3-pin for SWD	30-pin plus 6-pin ICSP header
User LED	Yes	Yes
Timer	Yes	No
Temperature sensor	Yes	No
Real-time clock (RTC)	Yes (but will require an external battery connection to maintain the clock)	No
Dimensions	51 × 21 mm	43.9 × 18.5 mm
Ground connections	8 (distributed)	2

***The Arduino Nano Every pin-compatible evolution of the original Arduino Nano features an enhanced ATmega4809 processor with twice the RAM of its predecessor.**

headers for direct mounting into a motherboard using an outer set of castellated pads and one that can be fitted with two 2-way headers using an inner set of plated-through holes (see Fig.8.1).

The GPIO pin assignment for the RPi Pico is shown in Fig.8.2. In common with other microcontrollers, pins are assigned different functions as required by a specific application. For example, pin-1 can be used as a general-purpose digital I/O line (GP0) as well as a serial communication transmit line (UART0), a serial peripheral interface receive line (SPI RX), or as a data line (I2C0 SDA) for inter-integrated circuit communication (I^2C).

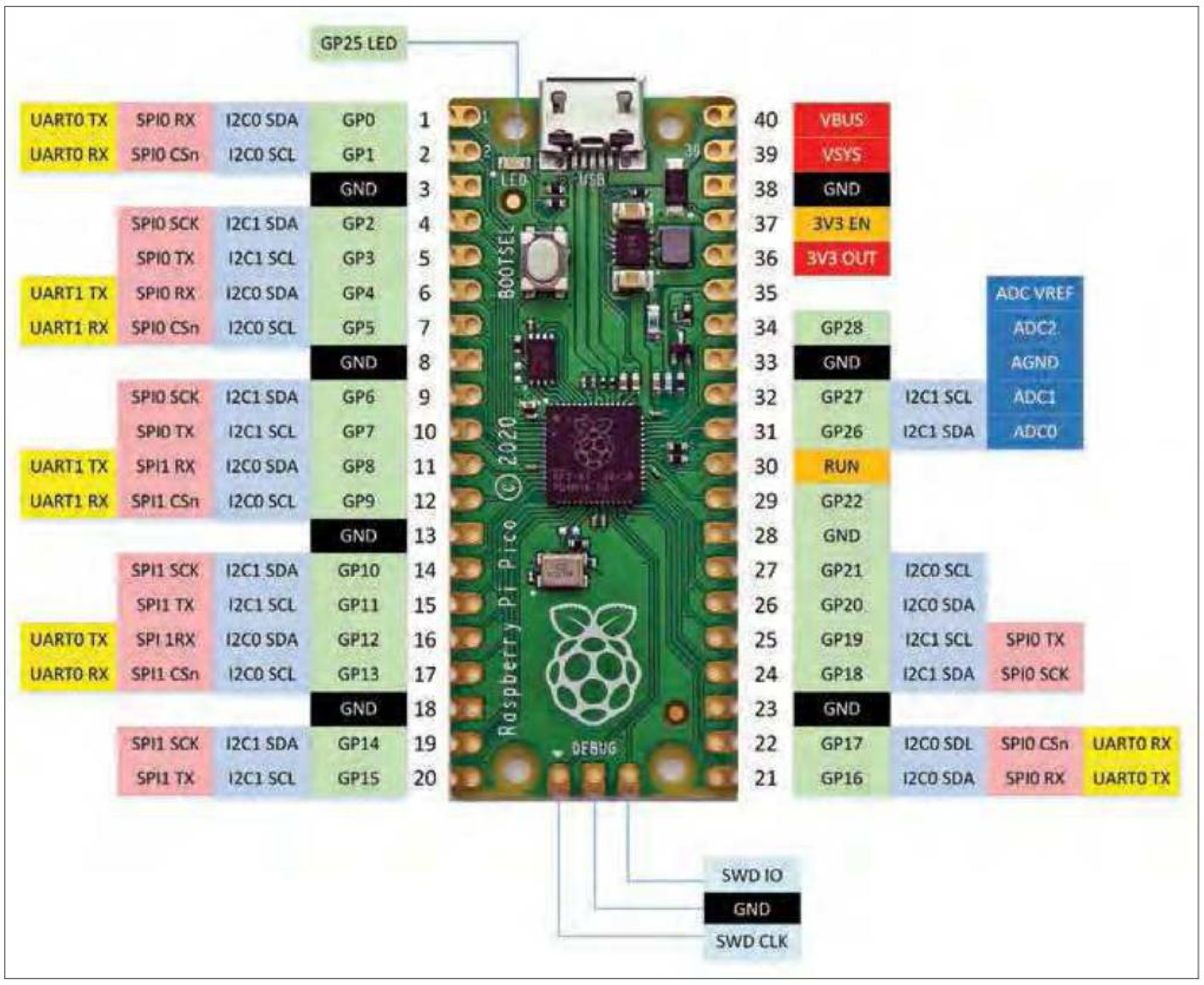

GP25 LED
UART0 TX
SPI0 RX
I2C0 SDA
GP0
1
UART0 RX
SPI0 CSn
I2C0 SCL
GP1
2
GND
3
SPI0 SCK
I2C1 SDA
GP2
4
SPI0 TX
I2C1 SCL
GP3
5
UART1 TX
SPI0 RX
I2C0 SDA
GP4
6
UART1 RX
SPI0 CSn
I2C0 SCL
GP5
7
GND
8
SPI0 SCK
I2C1 SDA
GP6
9
SPI0 TX
I2C1 SCL
GP7
10
UART1 TX
SPI1 RX
I2C0 SDA
GP8
11
UART1 RX
SPI1 CSn
I2C0 SCL
GP9
12
GND
13
SPI1 SCK
I2C1 SDA
GP10
14
SPI1 TX
I2C1 SCL
GP11
15
UART0 TX
SPI 1RX
I2C0 SDA
GP12
16
UART0 RX
SPI1 CSn
I2C0 SCL
GP13
17
GND
18
SPI1 SCK
I2C1 SDA
GP14
19
SPI1 TX
I2C1 SCL
GP15
20
40
VBUS
39
VSYS
38
GND
37
3V3 EN
36
3V3 OUT
35
ADC VREF
34
GP28
ADC2
33
GND
AGND
32
GP27
I2C1 SCL
ADC1
31
GP26
I2C1 SDA
ADC0
30
RUN
29
GP22
28
GND
27
GP21
I2C0 SCL
26
GP20
I2C0 SDA
25
GP19
I2C1 SCL
SPI0 TX
24
GP18
I2C1 SDA
SPI0 SCK
23
GND
22
GP17
I2C0 SDL
SPI0 CSn
UART0 RX
21
GP16
I2C0 SDA
SPI0 RX
UART0 TX
SWD IO
GND
SWD CLK

Fig.8.2. Pin assignment for the Raspberry Pi Pico's GPIO connectors.

The RPi Pico uses standard 3.3V logic and there's a total of 25 GPIO pins to play with. Three of the GPIO pins can be configured as analogue inputs (its RP2040 chip incorporates four 12-bit analogue-to-digital converters (ADC) but only three of them can be accessed from the outside world). In common with other budget microcontrollers, the Pico does not have true DAC capability. Instead, analogue output voltages can be produced by using pulse-width modulation (PWM) techniques via 16 of the GPIO pins with external low-pass filtering.

The Pico has an on-board regulator that generates the 3.3V supply bus from a 5V supply rail (see later). There's a single LED indicator available for user applications and a boot selector (BOOTSEL) button that's used to enter boot mode when the board is connected to a USB host device. Note that boot mode can also be entered by taking the RUN/Reset pin low (by shorting the pin to GND (0V). Note also that when the board enters boot mode the host computer will recognise it as a USB drive. This makes it very easy to update the RP2040's firmware.

The RP2040 chip

The RPi Pico is based on an RP2040 chip, a dual-core ARM Cortex M0+ running at clock speeds of up to 133MHz. The chip provides 30 multifunction GPIO pins that can be configured for several popular communication standards including I^2C, SPI, and UART, as well as the ADCs mentioned previously.

The RP2040 offers a reasonable amount of onboard RAM (264kB) but does not provide any internal Flash memory. Instead, this is provided by an external memory chip (see Fig.8.3) linked to the microcontroller by means of the Quad Serial Peripheral Interface (QSPI) bus. The QSPI bus uses four data lines (QSPI_SD0 to QSPI_SD3) and is consequently faster than the Serial Peripheral Interface (SPI) that only uses two data lines (MOSI and MISO). The external Flash memory has a 2MB capacity available for program, file and data storage, including that required to support the MicroPython language. Note that the RP2040 can support up to 16MB of external Flash memory and several manufacturers (including Pimoroni, Adafruit and SparkFun) have exploited this feature in their own microcontroller products (see Fig.8.4).

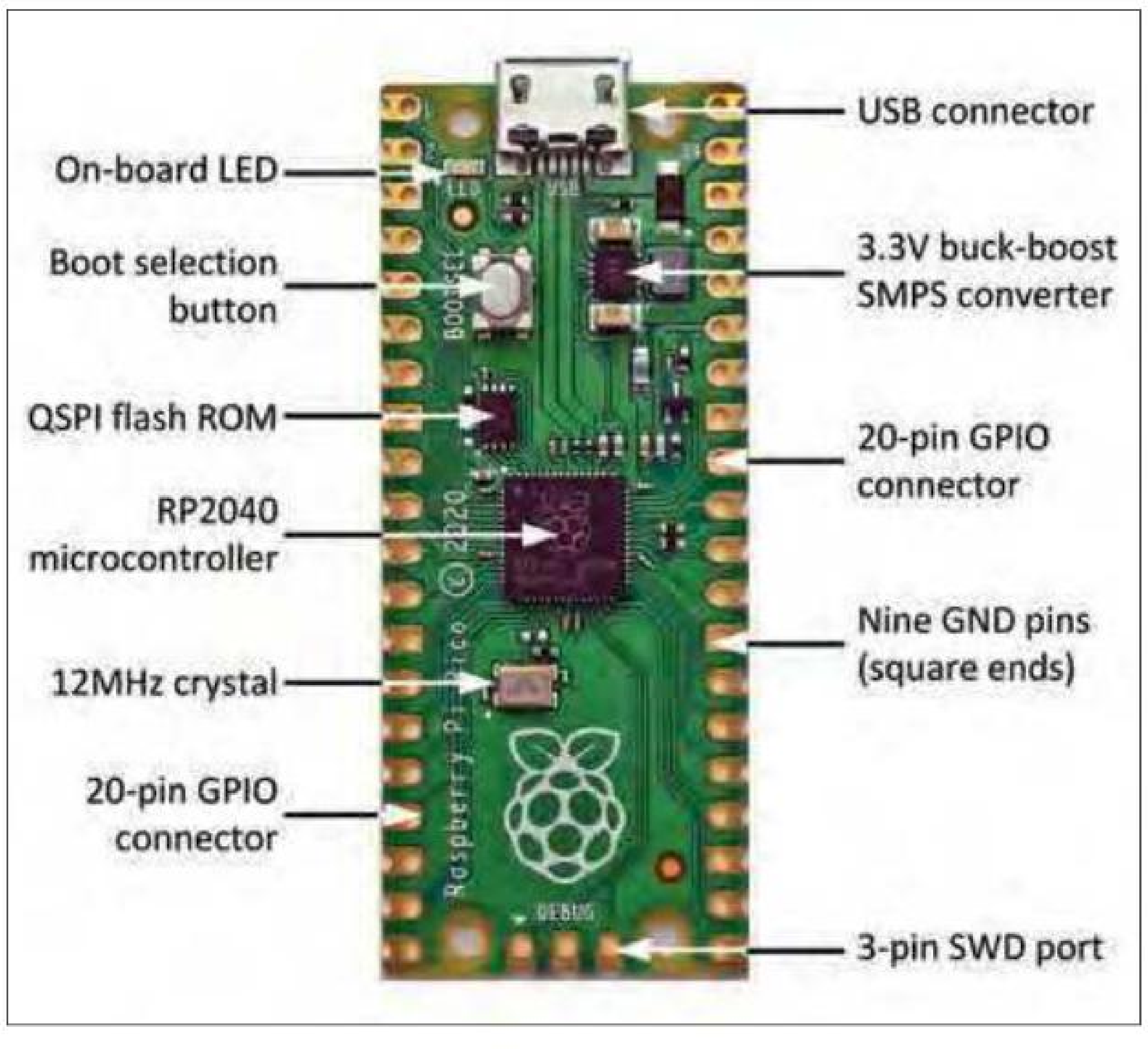

USB connector
On-board LED
Boot selection button
3.3V buck-boost SMPS converter
QSPI flash ROM
20-pin GPIO connector
RP2040 microcontroller
Nine GND pins (square ends)
12MHz crystal
20-pin GPIO connector
3-pin SWD port

Fig.8.3. Raspberry Pi Pico board layout.

The RP2040's eight PIO state machines make it possible to use custom hardware logic and data processing blocks that run independently of the CPU. This feature makes it possible to off-load processor-intensive tasks where large amounts of data, high data rates or accurate timing is required.

Coding and debugging the Raspberry Pi Pico

During programming, the RPi Pico appears as a mass storage device and files can be opened, edited, saved and executed in the normal way. Your work files are stored on the device itself, which keeps the coding process very straightforward (note that it is also important to keep backup copies of your work files on your PC).

The read, evaluate, print and loop (REPL) function will allow you to test fragments of code immediately and without the need to save your code. When connected and used in REPL mode a chevron prompt (>>>) appears in the integrated development environment (IDE) – see later.

Note that the USB port can be configured both as a host or as slave in USB 1.1 mode, supporting data transfer up to 12Mbit/s. This will allow you to attach a wide variety of USB peripherals as well as treating the board as a USB device for programming and REPL testing.

In common with other ARM Cortex processors, the R2040's Serial Wire Debug (SWD) port provides a means of debugging your code. The SWD port can be a very useful feature because it provides access to the chip's firmware,

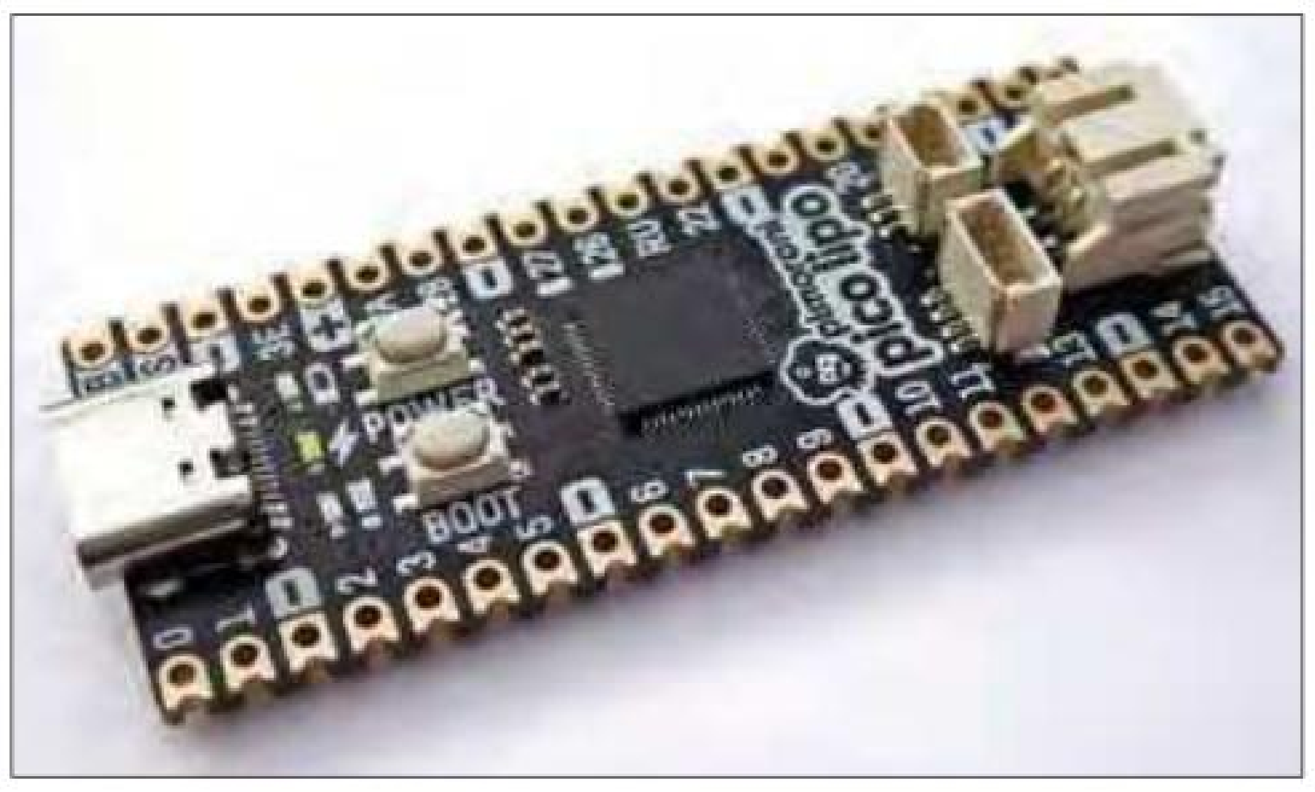
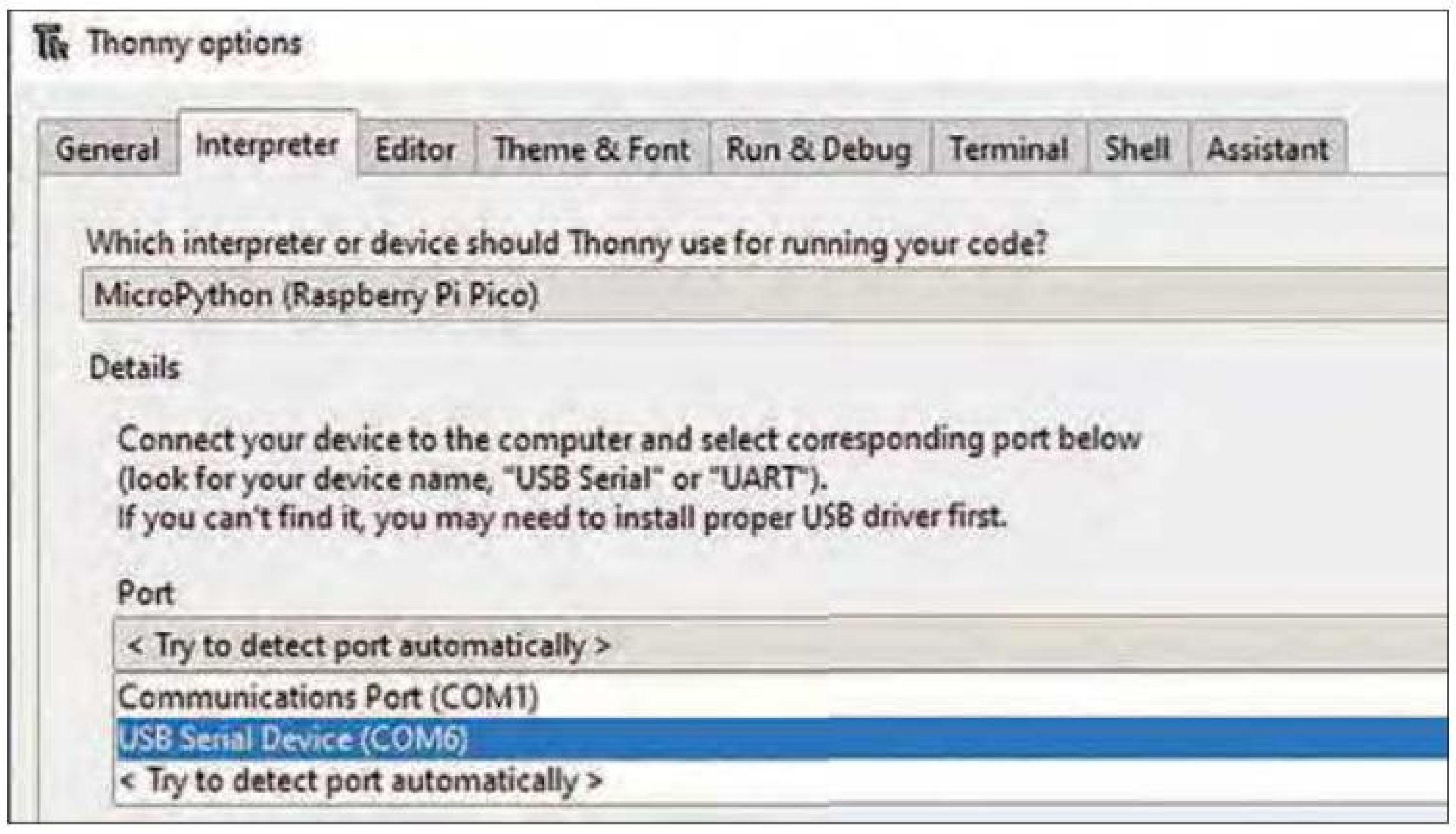


Fig.8.4. Pimoroni's PicoLipo retains chip and pin compatibility with the Raspberry Pi Pico but offers on-board battery management and a connector for an external 3.7V LiPo battery.



Which interpreter or device should Thonny use for running your code?

MicroPython (Raspberry Pi Pico)

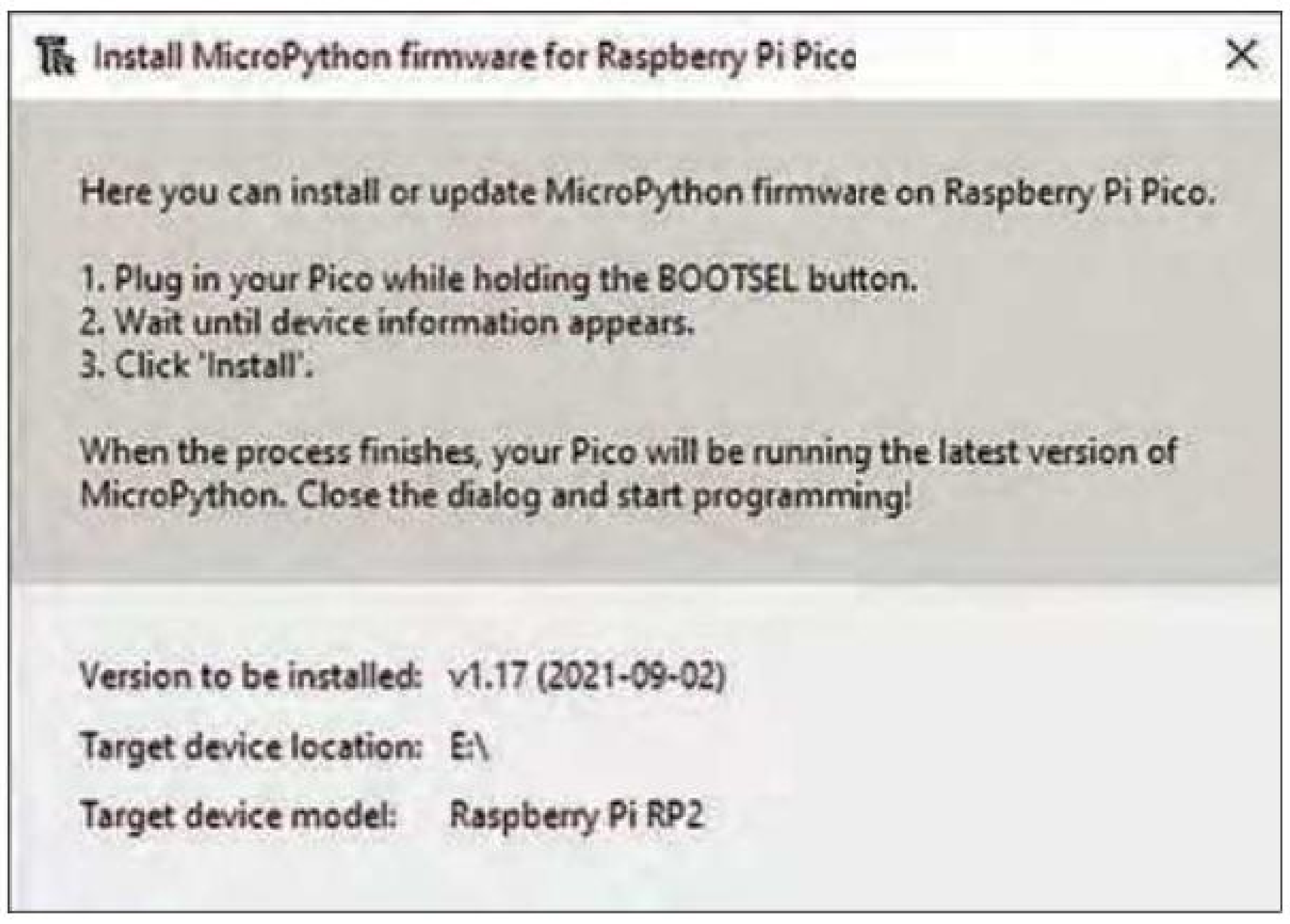
Details

Connect your device to the computer and select corresponding port below
(look for your device name, "USB Serial" or "UART").
If you can't find it, you may need to install proper USB driver first.

Port

< Try to detect port automatically >
Communications Port (COM1)
USB Serial Device (COM6)
< Try to detect port automatically >

(Left) Fig.8.5. Selecting Thonny's options.



Here you can install or update MicroPython firmware on Raspberry Pi Pico.

1. Plug in your Pico while holding the BOOTSEL button.
2. Wait until device information appears.
3. Click 'Install'.

When the process finishes, your Pico will be running the latest version of MicroPython. Close the dialog and start programming!

Version to be installed: v1.17 (2021-09-02)
Target device location: E:\
Target device model: Raspberry Pi RP2

(Right) Fig.8.6. Installing the MicroPython firmware.

allowing you to set breakpoints, trace execution and step through blocks of code. To make use of the serial debugging feature, a dedicated SWD probe must be connected to the SWD port which is separated from the rest of the GPIO pins and accessed at the bottom of the board (see Fig.8.3). Three physical connections are required: SWDIO (bidirectional data), SWCLK (clock), and GND (ground).

Power supply arrangements

One of the most interesting and potentially useful features of the RPi Pico is its ability to operate from multiple power sources, including:

- 5V supply via the on-board micro-USB connector
- External regulated 5V supply connected to the board's VSYS and GND pins
- Battery with a voltage in the range 1.8V to 5.5V.

In normal use during application development, power can be supplied through the USB cable connected to a host computer and no other supply will be required. When operated with other equipment the device can derive its supply from an existing regulated +5V rail. For autonomous operation in the field, the board can be powered from an external battery, in which case VSYS should typically be around 3.7V for a standard lithium polymer (LiPo) battery. However, due to the use of an on-board RT6150 buck-boost DC-to-DC converter (see Fig.8.3.) the input voltage applied to VSYS can range from as little as 1.8V to just over 5V, so instead of using a single 3.7V LiPo cell, two or three series-connected NiMH batteries can be connected. Note, however, that external battery management circuitry will be required for applications that use non-replaceable batteries (ie, where batteries cannot be removed for recharging).

Trying it out

In conjunction with an IDE, the RPi Pico is very easy to use. There are several excellent coding environments to choose from, but the author's favourite is 'Thonny' and this environment will already be familiar to most existing RPi users. Thonny is simple to use and makes the coding process relatively painless. To get started, visit **www.thonny.org** and download Thonny for your operating system. When you subsequently click the Install option you will be prompted to select a destination location, after which you can create a desktop icon.

When the desktop icon is clicked, the default Thonny window will appear. Now, while holding the Pico's 'Boot Sel' button, connect the USB cable from the Pico to a vacant port on your computer and finally release the 'Boot Sel' button. Next, click on 'Run' from Thonny's menu bar and 'Select Interpreter' and use the dropdown list to select 'MicroPython (RPi Pico)'. Finally, select the port to be used (see Fig.8.5) and enter the code in Listing 8.1 using Thonny's code editor.

Listing 8.1 MicroPython code for monitoring the internal temperature of an RPi Pico's RP2040 microcontroller.

```
# Print internal temperature (deg.C)
import machine
import utime
sensor = machine.ADC(4)
while True:
  value = sensor.read_16()/19859
  temp = 27 - 581 * (value - 0.706)
  print(temp)
  utime.sleep(2)
```

Installing the MicroPython firmware

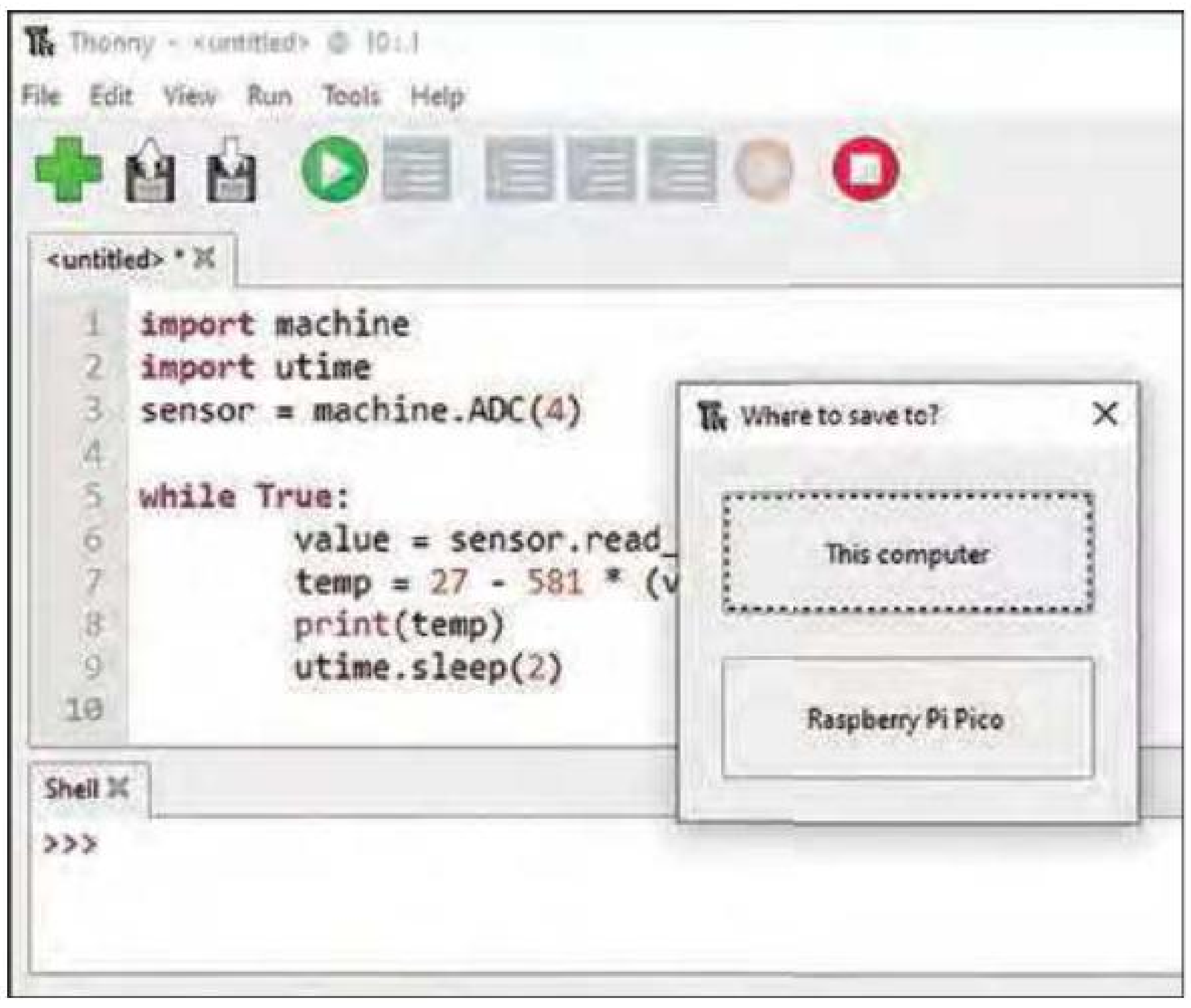
If you need to install the MicroPython firmware (see Fig.8.6) just click on 'Install' and wait for 'Done!' to appear and then close the window. The shell window will now appear with the REPL chevron prompt (>>>) at the bottom of the screen. Return to the editor window and then click on the 'Run' icon (the green circled arrow). When asked where to save the program, click on 'Raspberry Pi Pico' (see Fig.8.7).

Executing your code

Following the 'Run' command, your code will be executed and you should see the processor core temperatures appearing in the Shell window (see Fig.8.8). If this isn't the case, check that you've saved the code to the RPi Pico (not to the host computer) and that there are no error messages in the Shell window.

Adding an LCD

It's easy to add an LCD display to the RPi Pico using either the board's built-in I^2C or SPI interfaces (we've chosen the former simply because we have several 20x2



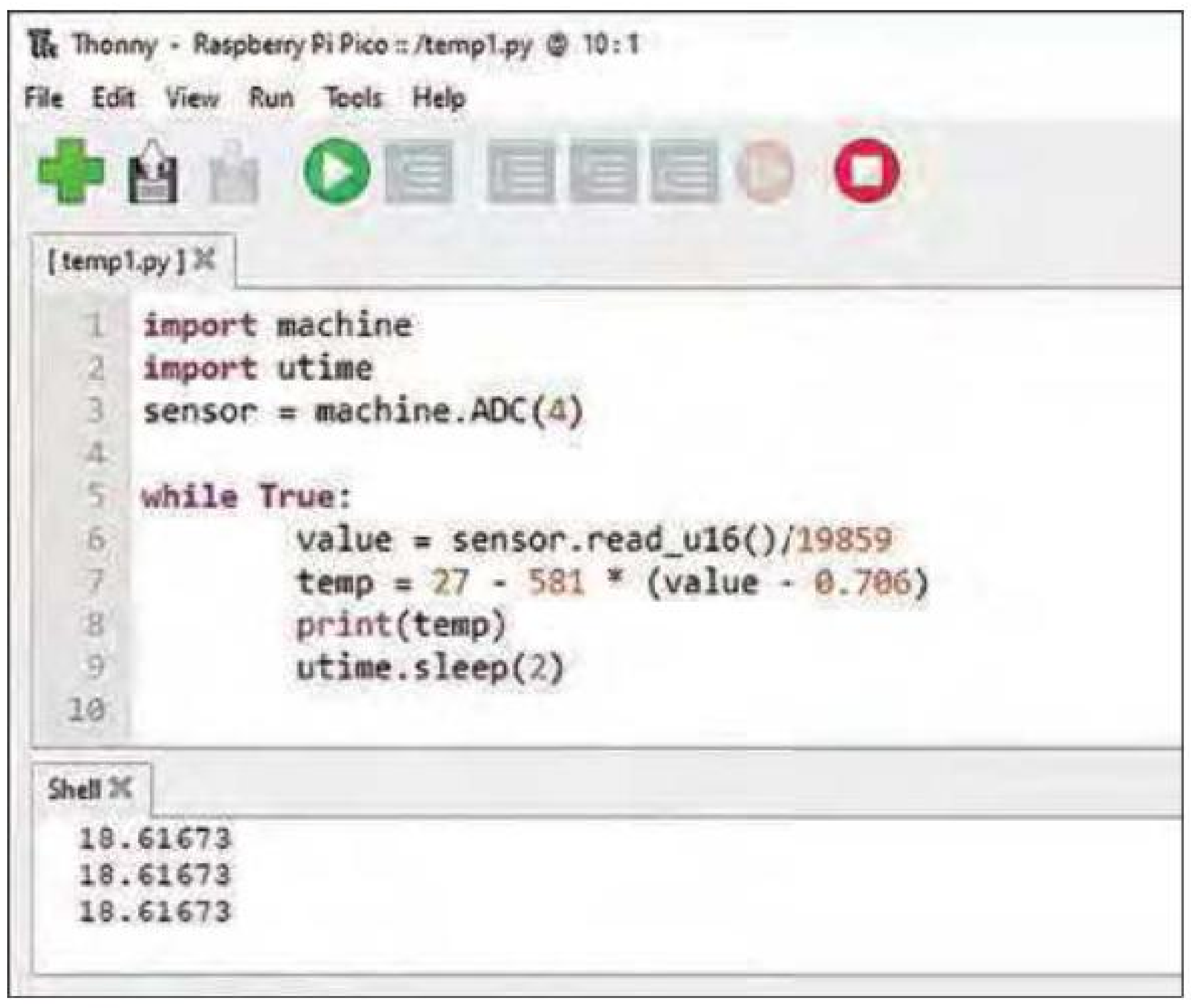
```
import machine
import utime
sensor = machine.ADC(4)

while True:
        value = sensor.read_
        temp = 27 - 581 * (v
        print(temp)
        utime.sleep(2)

```

```
>>>
```

Fig.8.7. Saving your MicroPython code.



```
import machine
import utime
sensor = machine.ADC(4)

while True:
        value = sensor.read_u16()/19859
        temp = 27 - 581 * (value - 0.706)
        print(temp)
        utime.sleep(2)

```

```
 18.61673
 18.61673
 18.61673
```

Fig.8.8. Results appearing in the Shell window.

LCD I^2C displays to hand). The required circuit arrangement is shown in Fig.8.9. Notice that there are just four connections from the RPi Pico to the LCD board. The MicroPython code is shown in Listing 8.2. Note that the code makes use of the I^2C library which supports communication between the RPi Pico and the LCD display. Fig.8.10 shows the results appearing on the LCD.

Listing 8.2 Pico MicroPython code: temperature display using a 16x2 I^2C LCD.

```
# Pi Pico temperature display using a 16x2 I2C LCD module

# Import required libraries
from machine import I2C,Pin,ADC
from pico_i2c_lcd import I2cLcd
from time import sleep

# Use the internal temperature sensor
sensor_temp = ADC(4)

# Get the current temperature
def get_temperature():
  reading = sensor_temp.read_u16() * 0.0000504
  temperature = 27 - (reading - 0.706)/0.001721
  temperature = round(temperature, 2)
  return temperature

# Initialise I2C port and LCD display
i2c = I2C(0, sda=Pin(0), scl=Pin(1), freq=100000)
lcd = I2cLcd(i2c, 39, 2, 16)

# Main loop to display temperature every four seconds
while True:
  lcd.putstr(“Temperature:\n”+str(get_temperature())+” deg.C”)
  sleep(4)
  lcd.clear()
```

Digital inputs and outputs

Digital inputs and outputs are easily handled using the `machine` library. For example, to read a button connected to GPIO Pin 0 and operate an LED connected to GPIO Pin 1 you would need something like the code shown in Listing 8.3. This code has an added delay using `time.sleep()` so the button must be held down for at least one second before the change of LED state occurs. The code has been commented and, as you can see, it is reasonably straightforward. To make things even easier we can make use of the `led.toggle()` function, as shown in Listing 8.4. Finally, a dedicated breadboard (like the one shown in Fig.8.11 – see *Going Further*) can be invaluable when experimenting with the RPi Pico.

Listing 8.3 Code for sensing the state of a button and operating an LED

```
from machine import Pin
import time

led = Pin(1, Pin.OUT)                   # LED connected to GPIO Pin 1
button = Pin(0, Pin.IN, Pin.PULL_DOWN)  # Button connected to GPIO
Pin 0

while True:
  if button.value():
    led.value(1)  # Turn the LED on
  else:
    led.value(0)  # Turn the LED off
  time.sleep(1)   # Hold button down for 1s
```

Listing 8.4 Improved code using the led.toggle() function

```
from machine import Pin
from utime import sleep
led = Pin(1, Pin.OUT)
button = Pin(0, Pin.IN, Pin.PULL_DOWN)
while True:
  if button.value():
    led.toggle()
    sleep(1)
```

Going Further

This section (overleaf) details a variety of sources that will help you locate parts and further information that will allow you to make good use of the Raspberry Pi Pico in your own projects. It also provides links to relevant underpinning knowledge and manufacturers' reference information.

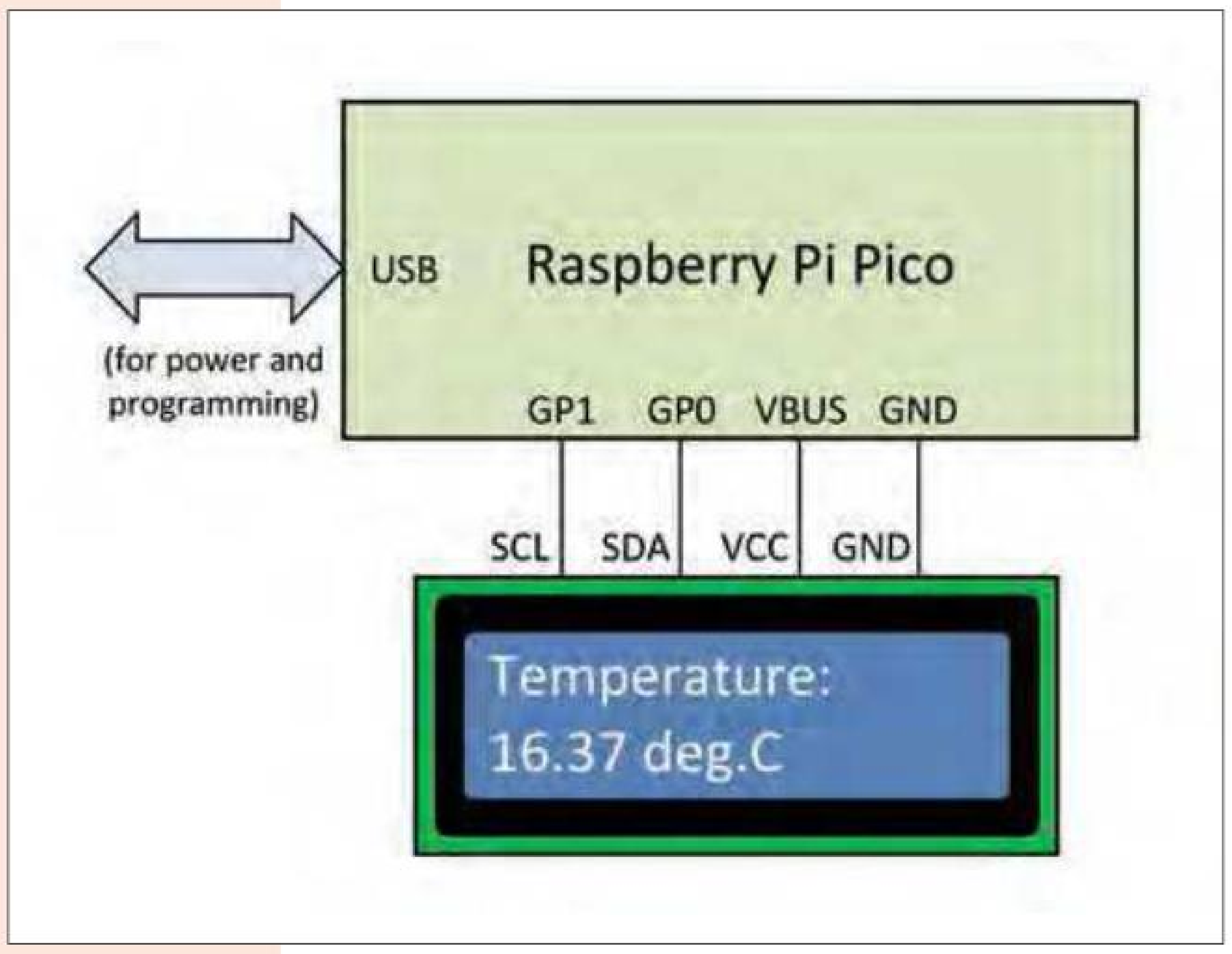


Fig.8.9. Circuit arrangement for adding an LCD.

Temperature:
16.37 deg.C

Fig.8.10. Results appearing on the LCD.

Fig.8.11. The excellent Raspberry Pi Pico breadboard from SB Components is an ideal platform for hardware experiments.

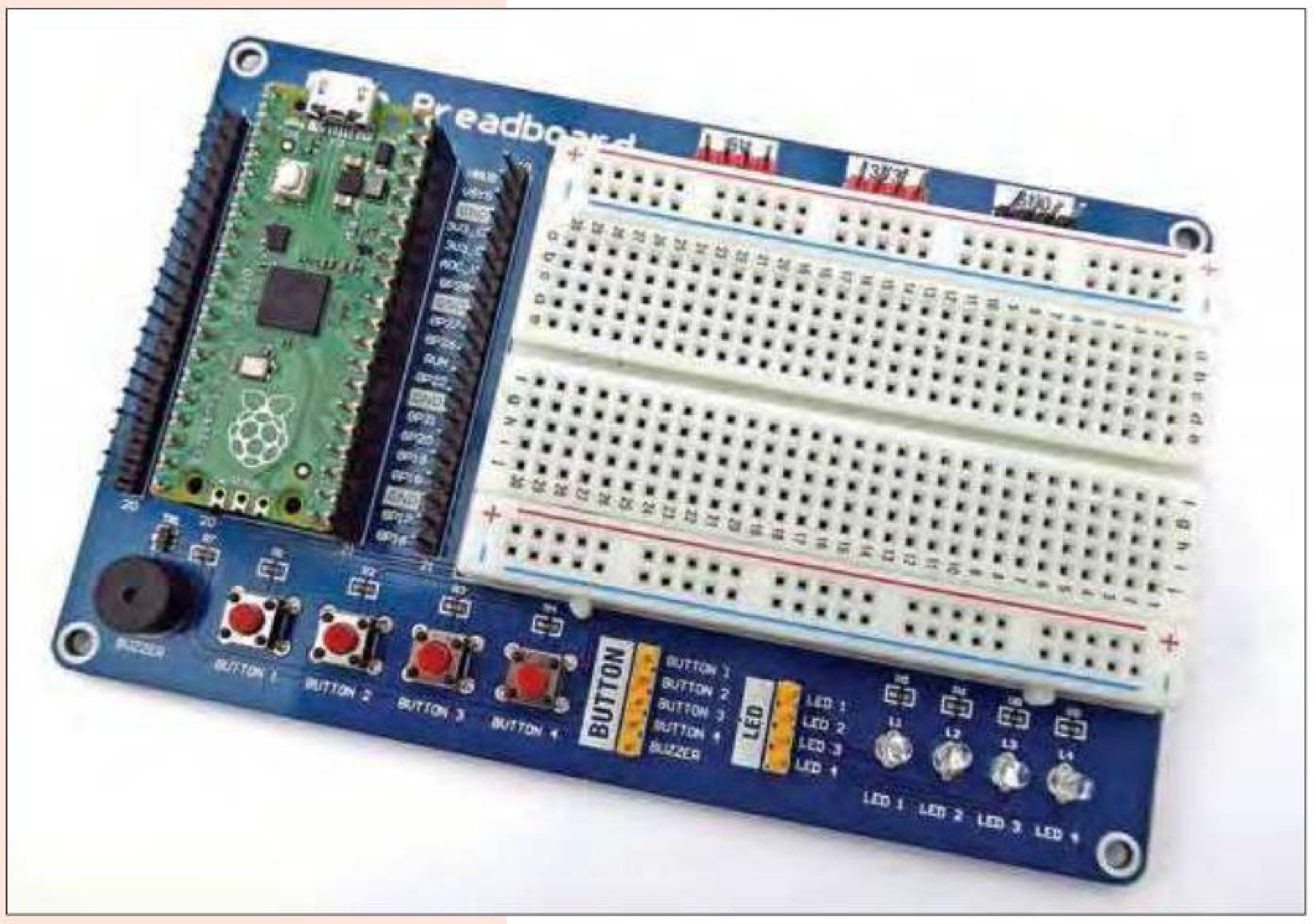


Table 8.2. Going Further with Raspberry Pi Pico

Topic	Source	Notes
RPi Pico boards	Numerous suppliers eg, The Pi Hut (**www.thepihut.com**) offer the RPi Pico boards, both with and without soldered headers.	Boards with headers cost more than those without. Soldering skills will be required if you intend to solder your own headers!
RPi Pico books	The official RPi Pico guide is *Get Started with Micropython on Raspberry Pi Pico* by Gareth Halfacre and Ben Everard (ISNB 978-1-912-04786-4). Introduction to the RPi Pico and Thonny, plus simple projects suitable for beginners. *Programming the Pico – Learn Coding and Electronics with the Raspberry Pi Pico* by Simon Monk (ISBN 979-8-464-88217-1) is another excellent introduction.	These two books are intended for complete beginners and they both assume little previous knowledge of electronics and coding.
RPi Pico projects	**https://bit.ly/pe-may22-pico1**	Useful beginners' guide to connecting an RPi Pico to a PC, installing the Thonny Python IDE, and writing a MicroPython program to blink the Pico's LED
RP2040	Official documentation for the RP2040 microcontroller IC: **https://bit.ly/pe-may22-pico2** RP2040 datasheet: **https://bit.ly/pe-may22-pico3**	The RP2040's datasheet is extremely detailed and runs to well over 600 pages!
Micro-Python	Latest MicroPython documentation: **https://bit.ly/pe-may22-pico4** Latest Thonny version for Windows, Mac or Linux: **www.thonny.org**	
Software debugging	Information on using the SWD interface with an RPi computer: **https://bit.ly/pe-may22-pico5**	Two useful guides to using SWD with an RPi Pico
RPi Pico breadboards and expansion boards	**https://shop.sb-components.co.uk/** **www.thepihut.com**	SB Components provide a variety of breadboards and expansion boards designed for the RPi Pico. Similar boards at the Pi Hut.

Fluke/Philips PM3092 Oscilloscope
2+2 Channel 200MHz Delay TB,
Autoset etc – £250

STEWART OF READING
17A King Street, Mortimer, near Reading, RG7 3RS
Telephone: **0118 933 1111** Fax: **0118 933 2375**
USED ELECTRONIC TEST EQUIPMENT
Check website **www.stewart-of-reading.co.uk**
(ALL PRICES PLUS CARRIAGE & VAT)
Please check availability before ordering or calling in

HP 54600B Oscilloscope
Analogue/Digital Dual Trace 100MHz
Only £75, with accessories £125

LAMBDA GENESYS	PSU GEN100-15 100V 15A Boxed As New	£400
LAMBDA GENESYS	PSU GEN50-30 50V 30A	£400
IFR 2025	Signal Generator 9kHz – 2.51GHz Opt 04/11	£900
IFR 2948B	Communication Service Monitor Opts 03/25 Avionics	POA
IFR 6843	Microwave Systems Analyser 10MHz – 20GHz	POA
R&S APN62	Syn Function Generator 1Hz – 260kHz	£295
Agilent 8712ET	RF Network Analyser 300kHz – 1300MHz	POA
HP8903A/B	Audio Analyser	£750 – £950
HP8757D	Scaler Network Analyser	POA
HP3325A	Synthesised Function Generator	£195
HP3561A	Dynamic Signal Analyser	£650
HP6032A	PSU 0-60V 0-50A 1000W	£750
HP6622A	PSU 0-20V 4A Twice or 0-50V 2A Twice	£350
HP6624A	PSU 4 Outputs	£400
HP6632B	PSU 0-20V 0-5A	£195
HP6644A	PSU 0-60V 3.5A	£400
HP6654A	PSU 0-60V 0-9A	£500
HP8341A	Synthesised Sweep Generator 10MHz – 20GHz	£2,000
HP83630A	Synthesised Sweeper 10MHz – 26.5 GHz	POA
HP83624A	Synthesised Sweeper 2 – 20GHz	POA
HP8484A	Power Sensor 0.01-18GHz 3nW-10µW	£75
HP8560E	Spectrum Analyser Synthesised 30Hz – 2.9GHz	£1,750
HP8563A	Spectrum Analyser Synthesised 9kHz – 22GHz	£2,250
HP8566B	Spectrum Analsyer 100Hz – 22GHz	£1,200
HP8662A	RF Generator 10kHz – 1280MHz	£750
Marconi 2022E	Synthesised AM/FM Signal Generator 10kHz – 1.01GHz	£325
Marconi 2024	Synthesised Signal Generator 9kHz – 2.4GHz	£800
Marconi 2030	Synthesised Signal Generator 10kHz – 1.35GHz	£750
Marconi 2023A	Signal Generator 9kHz – 1.2GHz	£700

Marconi 2305	Modulation Meter	£250
Marconi 2440	Counter 20GHz	£295
Marconi 2945/A/B	Communications Test Set Various Options	POA
Marconi 2955	Radio Communications Test Set	£595
Marconi 2955A	Radio Communications Test Set	£725
Marconi 2955B	Radio Communications Test Set	£800
Marconi 6200	Microwave Test Set	£1,500
Marconi 6200A	Microwave Test Set 10MHz – 20GHz	£1,950
Marconi 6200B	Microwave Test Set	£2,300
Marconi 6960B	Power Meter with 6910 sensor	£295
Tektronix TDS3052B	Oscilloscope 500MHz 2.5GS/s	£1,250
Tektronix TDS3032	Oscilloscope 300MHz 2.5GS/s	£995
Tektronix TDS3012	Oscilloscope 2 Channel 100MHz 1.25GS/s	£450
Tektronix 2430A	Oscilloscope Dual Trace 150MHz 100MS/s	£350
Tektronix 2465B	Oscilloscope 4 Channel 400MHz	£600
Farnell AP60/50	PSU 0-60V 0-50A 1kW Switch Mode	£300
Farnell XA35/2T	PSU 0-35V 0-2A Twice Digital	£75
Farnell AP100-90	Power Supply 100V 90A	£900
Farnell LF1	Sine/Sq Oscillator 10Hz – 1MHz	£45
Racal 1991	Counter/Timer 160MHz 9 Digit	£150
Racal 2101	Counter 20GHz LED	£295
Racal 9300	True RMS Millivoltmeter 5Hz – 20MHz etc	£45
Racal 9300B	As 9300	£75
Solartron 7150/PLUS	6½ Digit DMM True RMS IEEE	£65/£75
Solatron 1253	Gain Phase Analyser 1mHz – 20kHz	£600
Solartron SI 1255	HF Frequency Response Analyser	POA
Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
Thurlby TG210	Function Generator 0.002-2MHz TTL etc Kenwood Badged	£65

HP/Agilent HP 34401A Digital
Multimeter 6½ Digit £325 – £375

HP33120A	Function Generator 100 microHz – 15MHz	£350
HP53131A	Universal Counter 3GHz Boxed unused	£600
HP53131A	Universal Counter 225MHz	£350
Audio Precision	SYS2712 Audio Analyser – in original box	POA
Datron 4708	Autocal Multifunction Standard	POA
Druck DPI 515	Pressure Calibrator/Controller	£400
Datron 1081	Autocal Standards Multimeter	POA
ENI 325LA	RF Power Amplifier 250kHz – 150MHz 25W 50dB	POA
Keithley 228	Voltage/Current Source	POA
Time 9818	DC Current & Voltage Calibrator	POA

Marconi 2955B Radio
Communications Test Set – £800

AOShop

The home for specialist audio, analogue and historic components – provided by Jake Rothman, *PE's Audio Out* columnist. The AOShop is your best bet for classic analogue 'NOS' (new old stock) components, including all parts for *Audio Out* projects and designs.

Ge semiconductors

Small-signal PNP transistors

AC125, NKT214F, OC57 OC59	**£1.00**

Low-noise PNP transistors

GET106	**£2.50**

Small power PNP transistors

AC153, AC153K, AC188	**£1.50**

High-voltage PNP transistors

OC77, CV7001, ACY20	**£1.50**

TO3 PNP power transistors

OC22, CV7054 (OC23), OC25, OC35, OC36, AD143, AD149, AD161, AD162	**£2.00**
AD140	**£3.50**
AD149 matched pair	**£5.00**

RF PNP transistors

OC41, OC42, 2SA12, 2SA53,AF124, AF128, GET872A	**£1.50**

NPN transistors

OC139, OC140, ASY73, AC141K, AC176K, AC176	**£2.00**

Diodes

CV7049 (OA10), CG92 (OA91)	**£0.50**

Si semiconductors

Diodes

ZC5800 RF Schottky	**£0.20**

Low-noise silicon transistors

BFW16A, 2SC3071	**£1.50**
2SC2204, 2SD655	**£0.50**
ZTX651	**£0.30**

RF transistors (suitable for Theremin)

BF199	**£0.50**
BF245	**£0.60**

Audio power MOSFETs

Exicon 10N20, 10P20	**£6.50**
Hitachi 2SJ99, 2SK343	**£3.50**
Hitachi 2SJ 50, 2SK135	**£7.00**
Hitachi 2SJ56, 2SK176	**£8.50**

JFETs

BFW11, BFW10, TIS73L, J177, J113, U1994, U1898, 2SJ176	**£1.00**

MOSFETs

ZVP2106A	**£0.30**
Dual-gate 3SK45, BFS28	**£1.50**

Metal-cased transistors

BC143	**£0.35**
2N1711	**£0.50**
BCY71	**£0.30**
BC109C	**£0.60**

Amplifiers

TL082 dual JFET input op amp	**£0.25**
LM318 high-speed op amp	**£0.35**
µA709 metal-cased op amp	**£2.00**
5534H metal-cased op amp	**£3.00**
LM384, TDA2030A	**£1.50**
TAA435 (power amp driver)	**£1.20**

Synthesiser ICs

That/dbx 2180 VCA/VCF	**£6.00**
CA3080 VCA/VCF (vocoder)	**£2.80**
CA3082 VCA/VCF	**£4.00**
LM13600/ LM13700 VCA/VCF	**£2.00**
CA3086 transistor array	**£1.00**
PT2399 echo/delay	**£1.50**

Dual transistors

2N2639, 2N2223, 2N2910 (NPN)	**£4.00**
E401 (JFET)	**£4.00**
DMMT3904/6	**£0.50**

Loudspeakers

PE Mini-Monitor

Volt PE165 6.5-inch woofer (each)	**£85**
Morel MDT29 tweeter (each)	**£25**
Kit *pair* of PE165/MDT29 plus Volt crossover parts and PCBs	**£299**
Monacor DT-28N tweeter (each)	**£45**
Vifa 19mm BC20SC15-04 tweeter (each)	**£15**
Volt PE110 5-inch woofer (each)	**£75**

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1.2mH, 1.5mH, 2mH, 2.7mH, 0.5mH (tapped at 0.3mH) (each)	**£5.85**
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Fully assembled and tested high-quality speaker prototypes – ask for details

LS3/5As and other similar speaker systems (pair)	**£200-£350**

Fully tested reclaimed speakers

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Vifa TC26 1-inch tweeter (each)	**£15**

Low-price speakers

Celestion elliptical 6x4-inch 5Ω (Robert's Radio)	**£3.50**
Philips 4-inch 4070	**£2.00**
EMI 10x6-inch, 30Ω Alnico	**£10**
64mm 64Ω neodymium	**£1.20**
3.5-inch 25Ω	**£3.50**
5x3-inch elliptical 50Ω or 80Ω Alnico	**£3.50**
1.65x2.75-inch 8Ω	**£1.50**

Can't see what you want? Just ask – we have a huge stock of inexpensive high-quality parts!

Capacitors

Note '10/63' denotes '10µF 63V'.

Polyester

3.3/100, 4.7/250, 4.7/63	**£1.00**
5.6/63, 8.2/63, 10/63	**£2.00**
Mullard 'Mustard' C296 0.22/400	**£2.00**

Polycarbonate

Axial 2.2/63 1%, 4.7/160, 6.8/63	**£1.00**

Radial

6.8/160V, 10/63	**£2.00**
Reclaimed 22/63	**£2.00**

Polystyrene

Philips 1% 4.7nF/160, 6.2nF/500, 12nF/63, 22nF/63, 110nF/63	**£1.00**
RIFA 1% 100nF/100	**£2.00**
Suflex 2.5% 10nF/63 (rad. or ax.)	**£0.50**

Radiation resistant

Siemens cellulose acetate MKL 2.2/25	**£0.80**

Electrolytic – Mullard blue 017 series

10/25, 22/25, 100/10	**£0.50**
150/40, 470/40,1000/40	**£1.00**

Tantalum – metal cased

22/50, 47/35, 68/25, 100/20, 120/10, 150/16, 220/10, 330/6	**£2.00**
22/35, 33/35, 47/20, 68/15, 100/10, 150/6	**£1.25**
4.7/50, 6.8/35, 10/25, 10/35, 22/15	**£1.00**

Moulded-case tantalum

Kemet axial 6.8/10	**£0.30**
Kemet radial 33/10	**£0.40**
STC radial 100/20	**£1.50**

Tantalum bead

22/50	**£1.00**
470/3	**£2.00**
680/6.3	**£3.00**

Wet tantalum

220/25 axial	**£3.20**
Castanet button 140/30, 470/3	**£3.20**
Hughes 540/10	**£3.20**

Bipolar

Hermetic bipolar tantalum 16/35	**£3.20**
Callins Elcap wet aluminium 10/50	**£0.50**

Philips solid-aluminium (axial) 121/123

47/16	**£1.00**
330/6.3	**£2.00**
100/35	**£4.00**

Philips Pearl 122 series (radial)

10/16	**£0.30**
10/25	**£0.50**

Silvered mica (radial)

4.7nF/500 5%	**£1.00**

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Vishay plastic-film 4-40pF	**£0.80**
Vishay plastic-film 5.5-45pF	**£1.00**
Vishay plastic-film 5-80pF	**£1.20**
Vishay plastic-film 10-250pF	**£2.00**
Mica 1-12pF, 2-40pF	**£1.00**

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Eagle transformers

LT44, LT722 driver, LT700, LT723 500Ω output	**£2.50**
LT30 500mW output	**£3.50**

Repanco

T/T3 splitter transformer	**£4.00**
CH2 5mH RFC	**£2.00**

Balanced output transformer

Vigortronix 600Ω VTX-101-007	**£10**
Vigortronix 600Ω VTX-101-3001	**£10**
Vigortronix 600Ω VTX-101-3002	**£15**
Gardners 150Ω	**£10**
Reclaimed BBC LL74/MPC nickel core 600Ω	**£12**

Reclaimed mic input transformer	**£15**

Inductors

82µH, 4.7mH, 100µH, 270µH	**£2.00**
7-inch ferrite rod with MW and LW windings	**£3.00**

Special resistors

Bourns wire-wound trimmer 5kΩ 3059 JM panel-mount	**£2.00**
Thermistor RA53, A13	**£4.00**
Thermistor CZ1, CZ6	**£1.50**
Holco H2 2.2MΩ 1W, 1%	**£1.00**
Welwyn 1GΩ 2W	**£1.00**
Allen Bradley 1.2kΩ 2W C-comp	**£1.00**

Lots of big valve resistors available.

Potentiometers

Bourns 81

25kΩ lin cermet	**£2.00**
25kΩ lin conductive plastic	**£3.00**

Plessey moulded-track

5kΩ log with switch	**£3.00**
50kΩ A/log	**£3.00**
Mil 250kΩ lin dual	**£5.00**

Alpha

16mm 4.7kΩ A/log	**£0.80**
220kΩ A/log	**£0.80**
10kΩ lin centre-detent dual-gang	**£1.50**

Allen Bradley J series/Honeywell 10kΩ lin 1 million cycles	**£5.00**
Blore Edwards AB 45 dual 5kΩ A/log with switch	**£3.50**
Alps RK9 dual-gang 5kΩ RD law	**£4.00**
BI P260 500kΩ log conductive plastic 1 million cycles	**£3.00**
Colvern wire-wound 100kΩ or 50kΩ dual-gang 3W	**£8.00**
Mil Spec hermetic 10Ω	**£8.00**

Miscellaneous

Theremin Clearance Sale!

Elysian Theremin MIDI box	**£300**

PCBs

Pocket Theremin (*EPE*, 1996)	**£4.00**
Elysian Theremin (*EPE*, 1996)	**£12**
Synth VCF, VCO (*EPE*, 2017)	**£3.00**
48V PSU (*EPE*, 2019)	**£3.00**

Relays

STC hermetic 4190 24V DPDT	**£4.00**

Switches Blore Edwards/Plessey

MH1 4-pole 3-way	**£3.00**
Elma 01 2-pole 6-way	**£6.00**
3PDT guitar pedal stomp switch	**£2.50**

Valves

EC88, PCL84	**£3.00**

Robert's Radio modules

Tuners LP1169, LP1179	**£7.00**
IF strip LP1171	**£7.00**

Knobs – large Bakelite

Bulgin 1960s and Sifam 1970s	**£1.50**

Contact
Jake Rothman
The Old Rectory, Arlais Road,
Llandrindod Wells, Powys
LD1 5HE (visit by appointment)
+44 (0)1597 829102
jrothman1962@gmail.com

Minimum order £5.00 inc post
Quantity discounts negotiable

Payment
PayPal, cards (via phone), bank transfer, cheques (payable to 'J Rothman', UK pounds only)
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Postage
Small Jiffy bag £2.99
Small package £4.99
Big boxes and overseas at cost – ask for a quote

AUDIO OUT

By Jake Rothman

Analogue Vocoder – Part 7: Assembly and testing

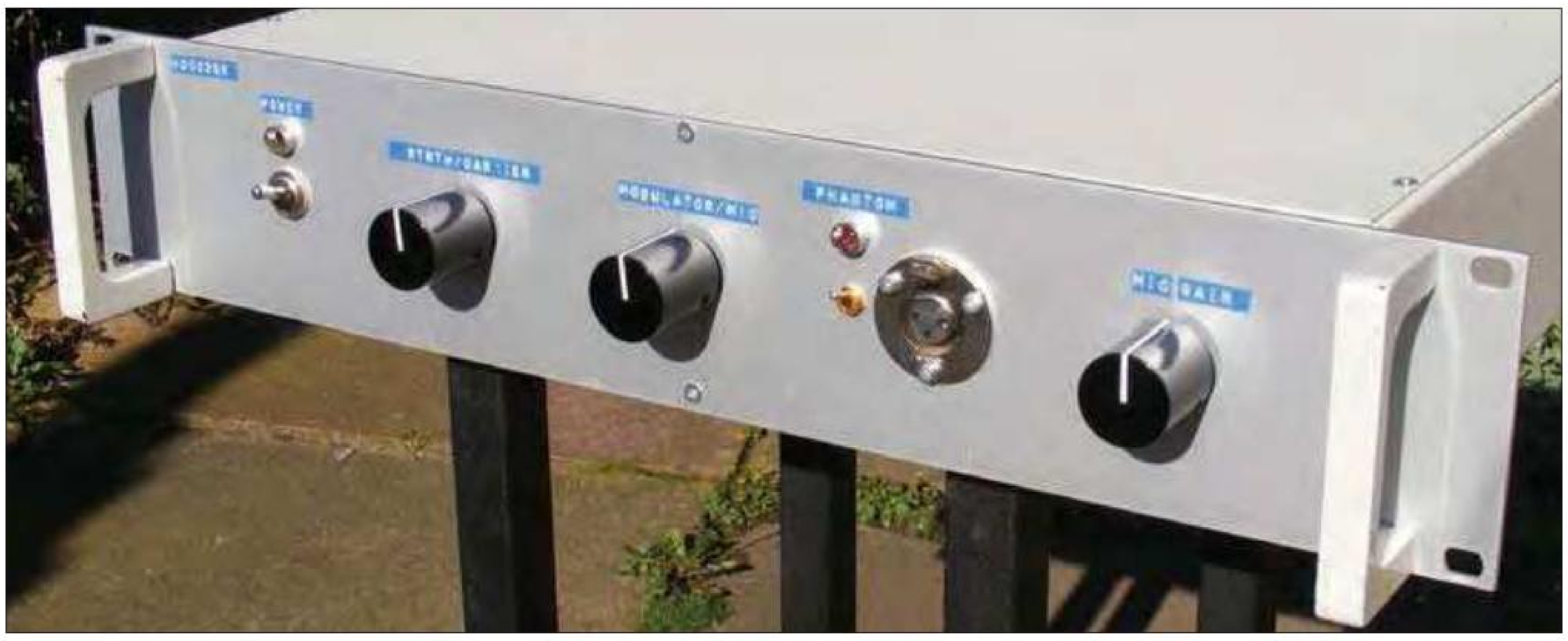


Fig.1. A finished Vocoder – with all the bells and whistles – what we've been aiming for all these months!

At last! – we've reached the stage where we can 'box-up' the *Vocoder*. Putting electronics in boxes or housings can be quite fraught for those who've only ever assembled PCBs. The construction techniques described here are applicable to all professional audio projects.

Little gremlins

First, a little housekeeping. In a project this complex a few errors can creep in, so please accept my apologies for the following corrections and amendments.

In last months' power supply (April 2022, Fig.10), the PCB overlay shows two D19s. The one on the right next to C24 should be D18 (a 10V Zener diode). Since this was a transcribing error from the Eagle CAD PCB file to the drawing, the silkscreen on the PCBs supplied by *PE* is correct. There were also two errors in the component list. D18 (see above) was incorrectly listed as D19. In the list, the 5.6V Zener diode was given as D18 – it should be D13.

I also have a few images that we couldn't squeeze into last month's PSU article. Fig.2 shows the final version of the PSU PCB (the one available from the *PE PCB Service*)

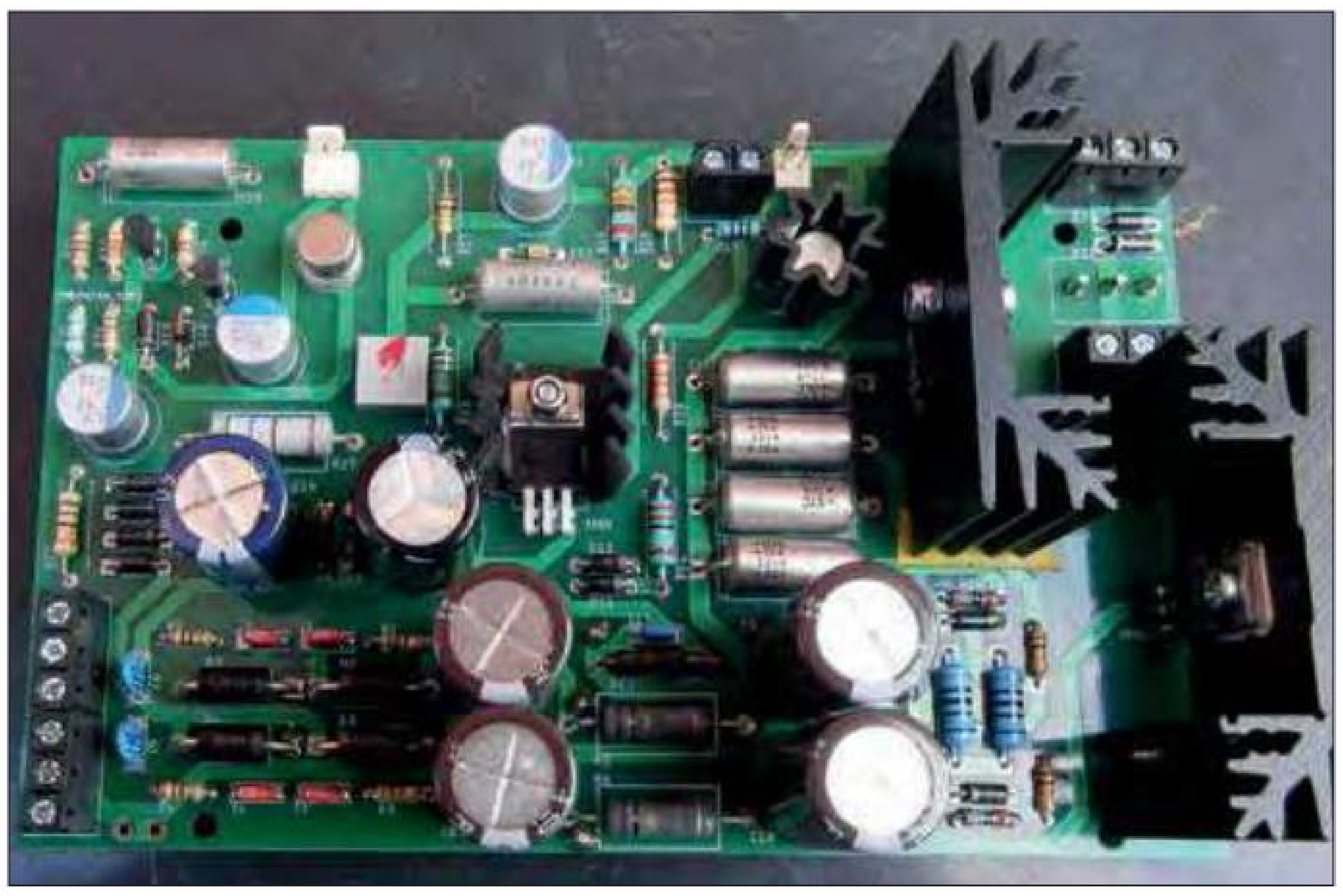
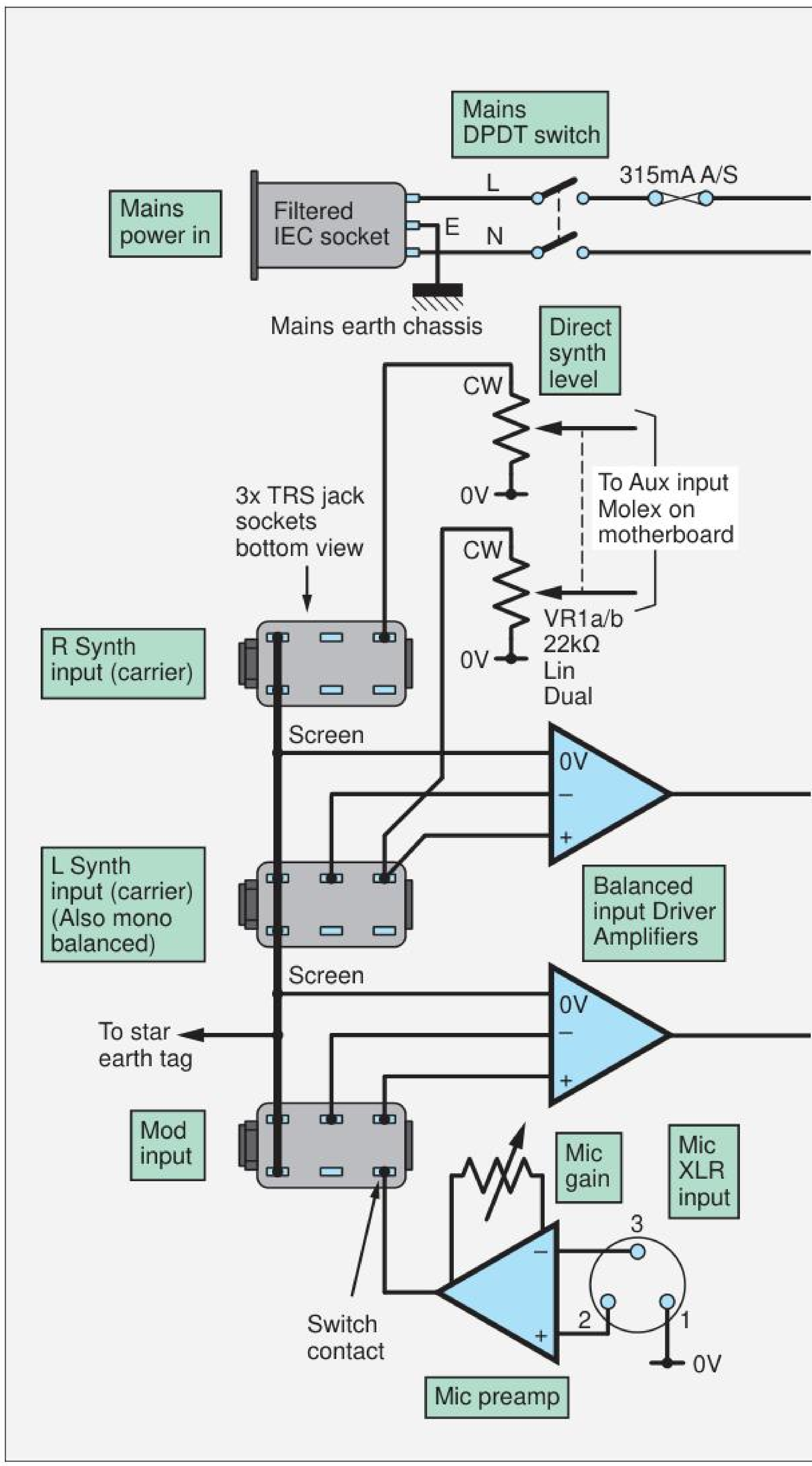
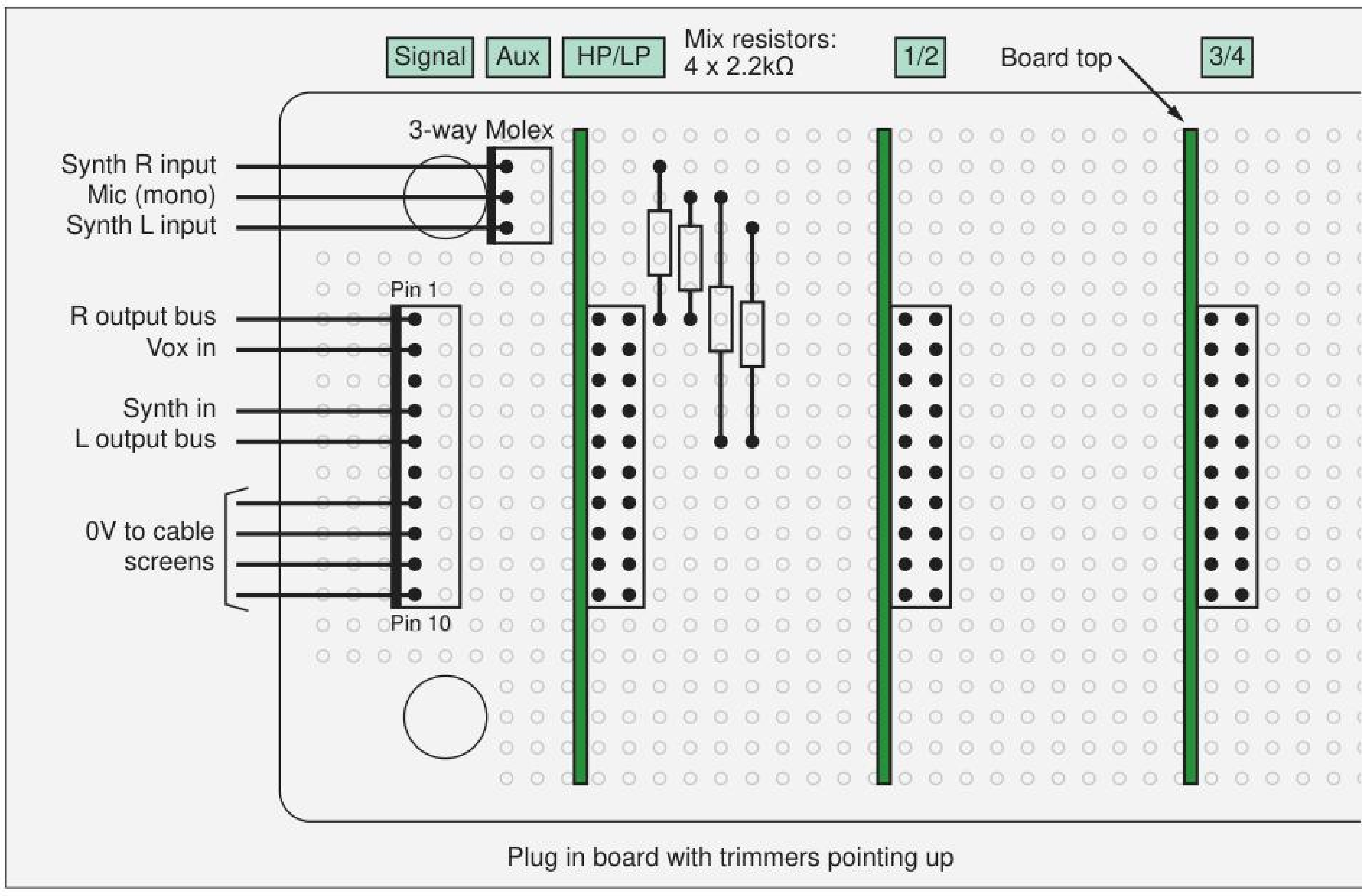


Fig.2. Updated power supply board from the April 2022 issue. This one uses only six wet Nichicon electrolytic capacitors. All the other smaller polarised capacitors are solid types. This reduced the residual ripple in the dual rail by 50%, and the phantom power by 75%. The capacitor life expectancy will now be 40,000 hours at 75ºC. The initial cost of this upgrade is about £15, but the labour cost and downtime for a capacitor change would be much more.


Mains DPDT switch
Mains power in
Filtered IEC socket
L
E
N
315mA A/S
Mains earth chassis
Direct synth level
CW
0V
CW
0V
3x TRS jack sockets bottom view
To Aux input Molex on motherboard
VR1a/b 22kΩ Lin Dual
R Synth input (carrier)
Screen
0V
–
+
L Synth input (carrier) (Also mono balanced)
Balanced input Driver Amplifiers
Screen
0V
–
+
To star earth tag
Mod input
Mic gain
Mic XLR input
3
–
+
2
1
0V
Switch contact
Mic preamp


Signal
Aux
HP/LP
Mix resistors: 4 x 2.2kΩ
1/2
Board top
3/4
3-way Molex
Synth R input
Mic (mono)
Synth L input
Pin 1
R output bus
Vox in
Synth in
L output bus
0V to cable screens
Pin 10
Plug in board with trimmers pointing up

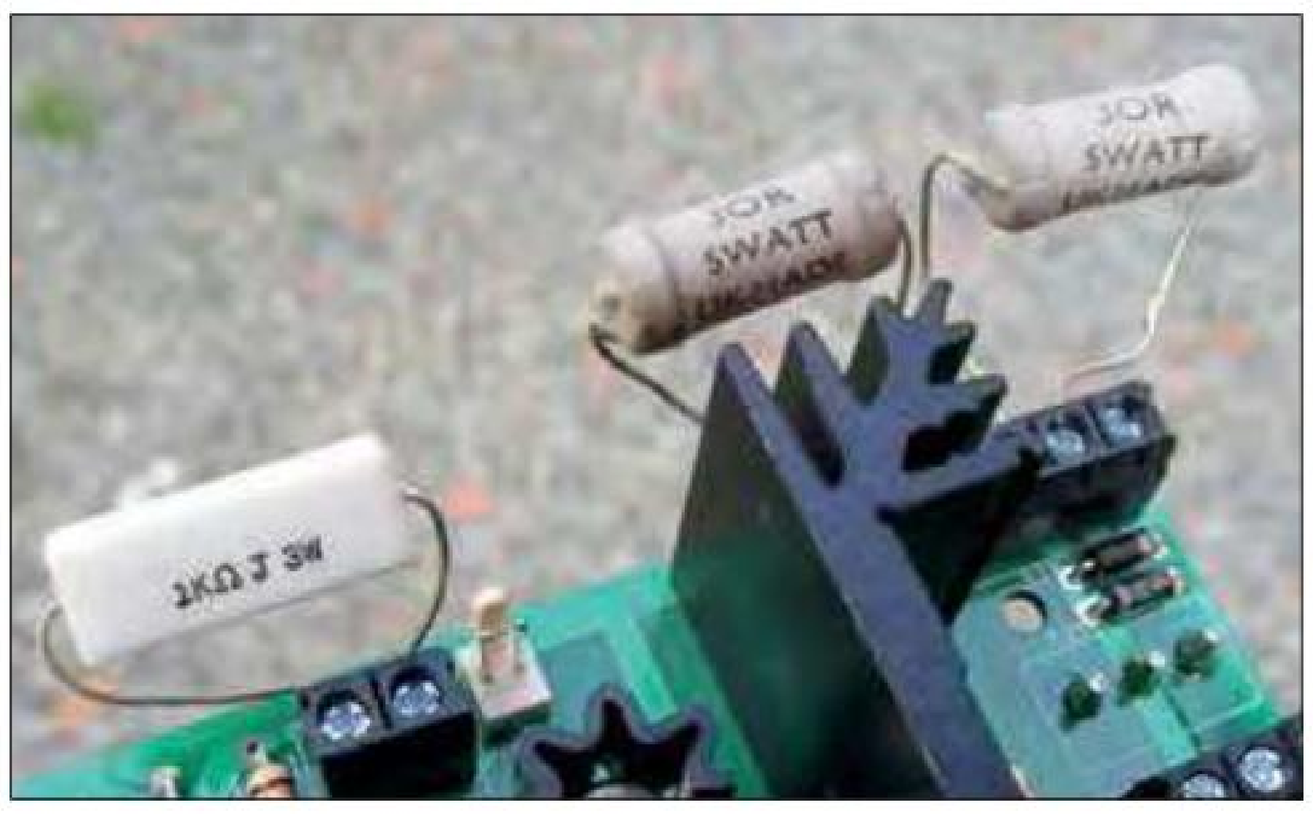
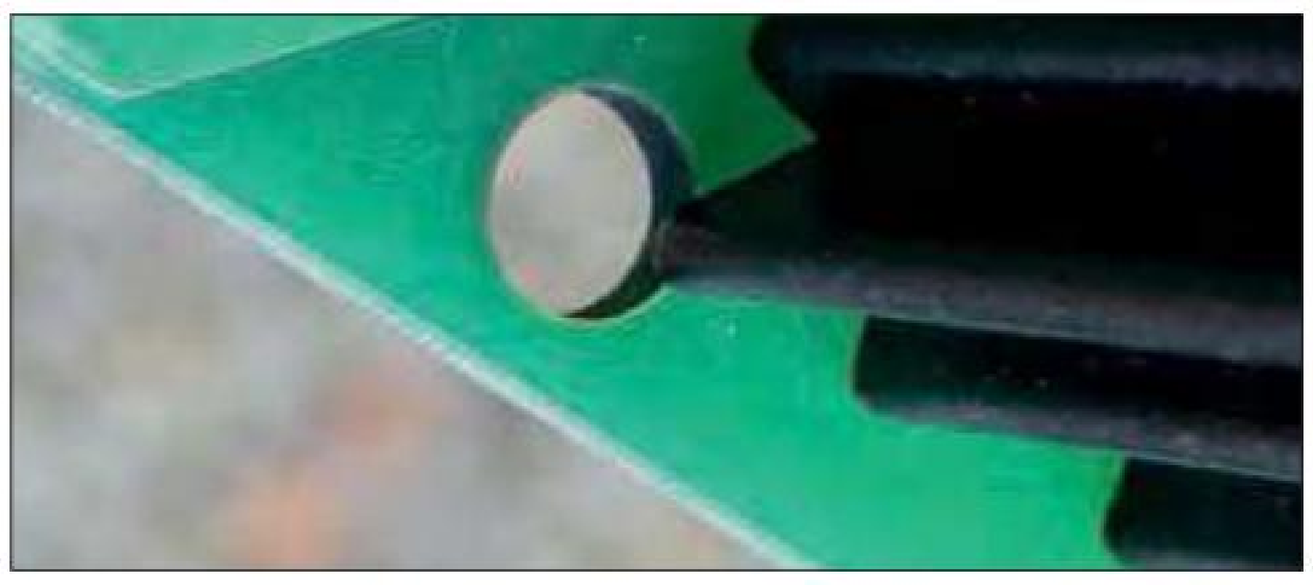


Fig.3. The final test of the power supply: loading the output rails with high-power wire-wound resistors. Always ‘cook’ boards before any in-service burn-in. This weeds out prematurely failing components and/or bad heatsink clamping.



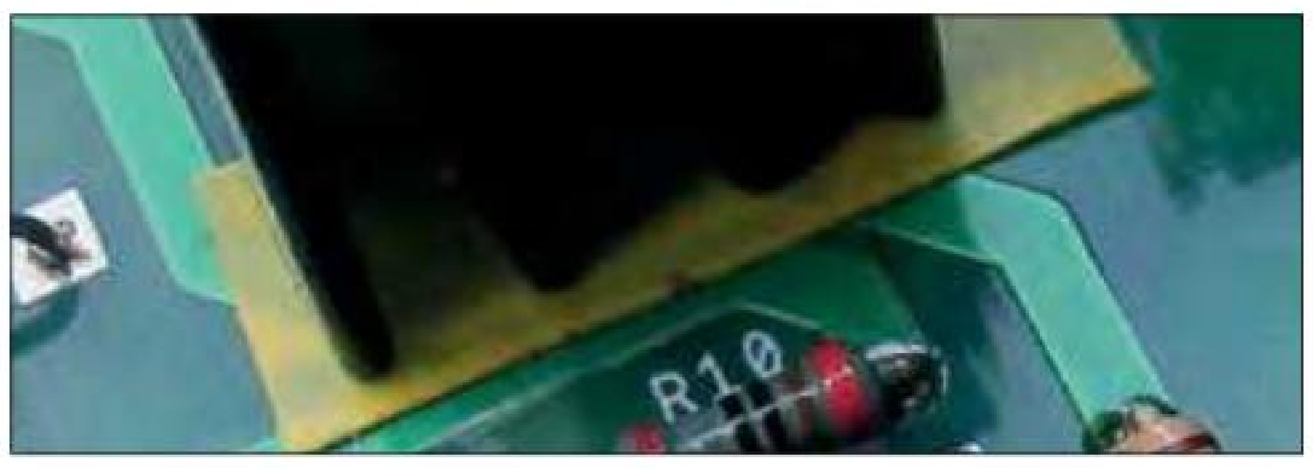


Fig.4. Tape should be placed under the heatsink to insulate it from the track. I’m not sure how tough the solder resist is.

Fig.5. (Left) It’s well worth filing IC2’s heatsink to clear the mounting hole. (Or, use a plastic bolt or drill another hole.)

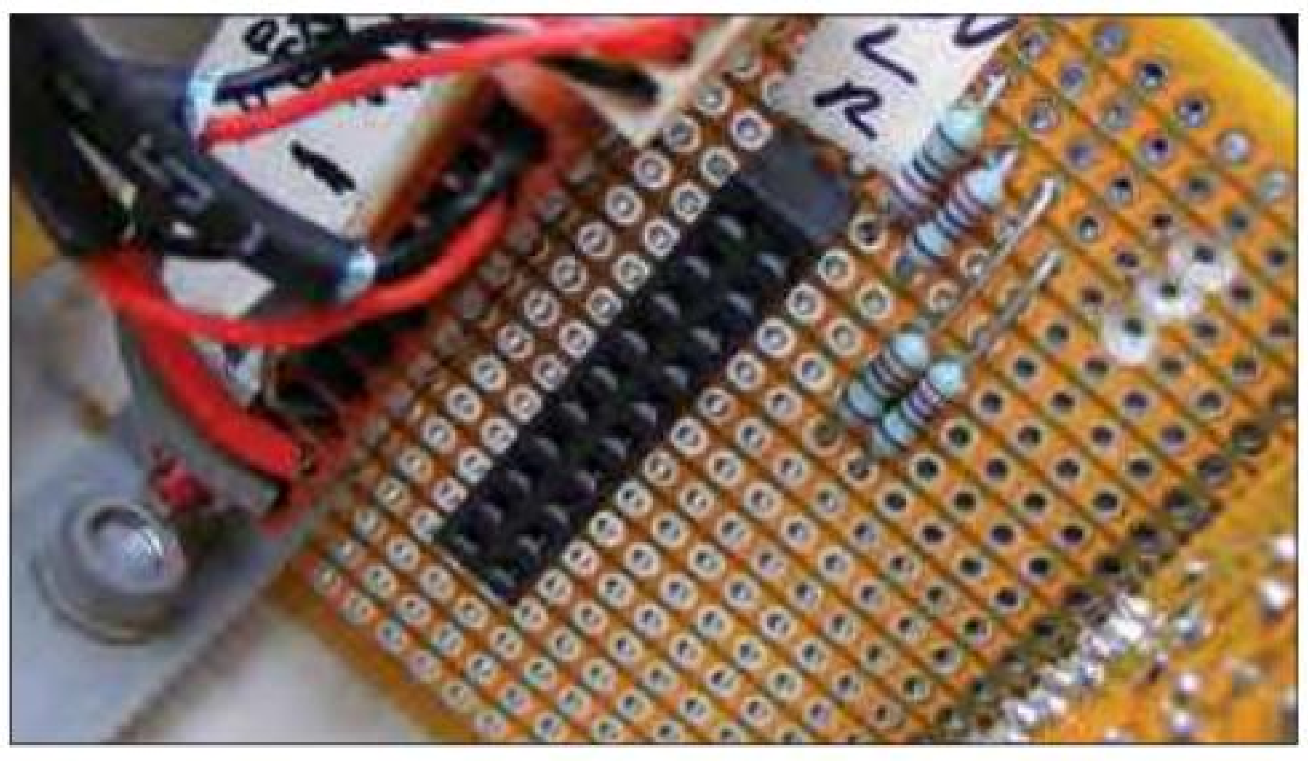


Fig.8. Motherboard showing cut track and how extra mix input resistors can be added to the mix busses.

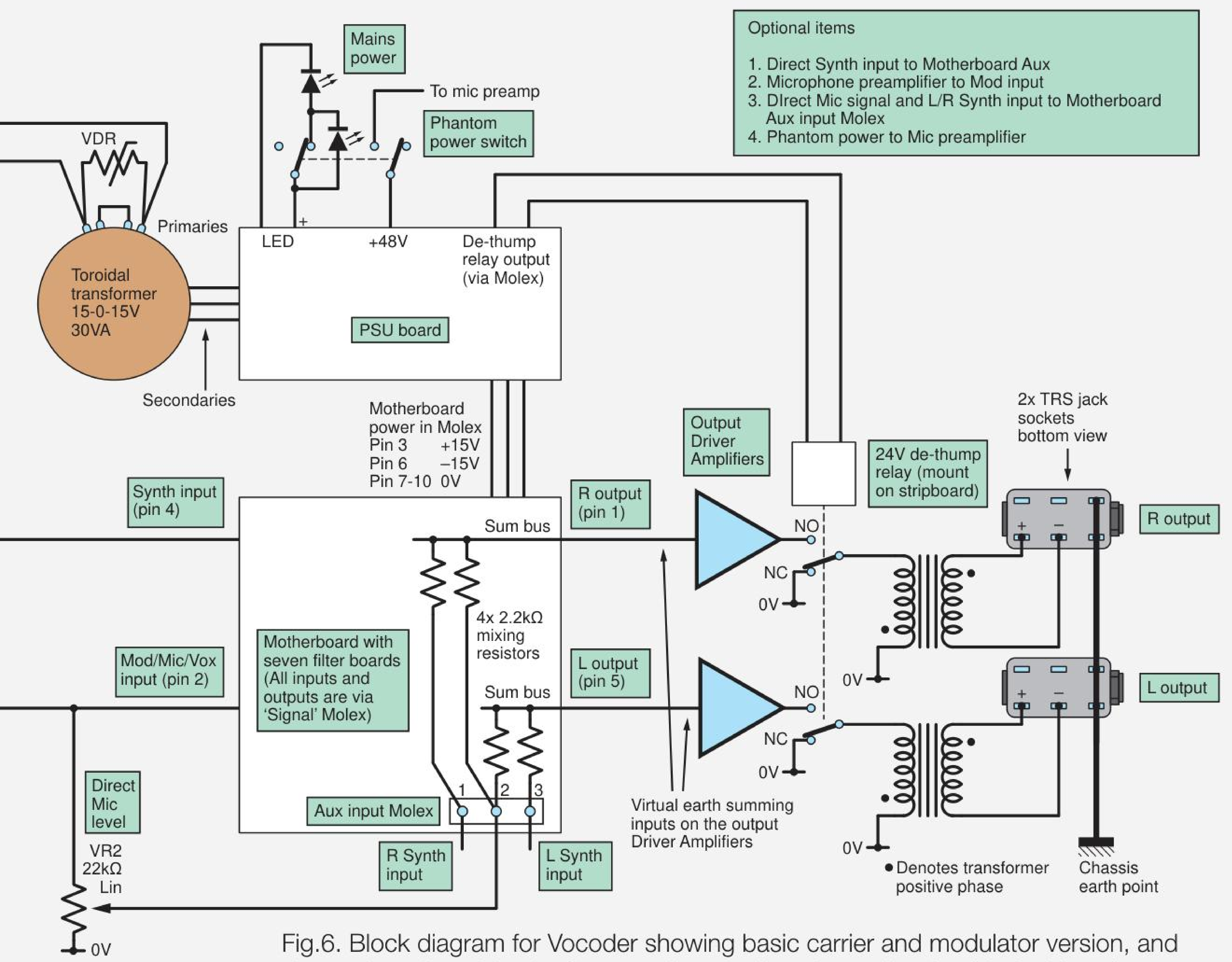

Mains power
To mic preamp
Phantom power switch
VDR
Primaries
Toroidal transformer 15-0-15V 30VA
Secondaries
LED
+48V
De-thump relay output (via Molex)
PSU board
Optional items
1. Direct Synth input to Motherboard Aux
2. Microphone preamplifier to Mod input
3. DIrect Mic signal and L/R Synth input to Motherboard Aux input Molex
4. Phantom power to Mic preamplifier
Motherboard power in Molex
Pin 3 +15V
Pin 6 –15V
Pin 7-10 0V
Synth input (pin 4)
Sum bus
4x 2.2kΩ mixing resistors
Motherboard with seven filter boards (All inputs and outputs are via ‘Signal’ Molex)
Mod/Mic/Vox input (pin 2)
Sum bus
Direct Mic level
VR2 22kΩ Lin
0V
Aux input Molex
1
2
3
R Synth input
L Synth input
Output Driver Amplifiers
R output (pin 1)
L output (pin 5)
NO
NC
0V
NO
NC
0V
24V de-thump relay (mount on stripboard)
0V
0V
2x TRS jack sockets bottom view
+
–
R output
L output
Virtual earth summing inputs on the output Driver Amplifiers
● Denotes transformer positive phase
Chassis earth point

Fig.6. Block diagram for Vocoder showing basic carrier and modulator version, and also options for mixing in direct synth and microphone signals with the Vocoder output.

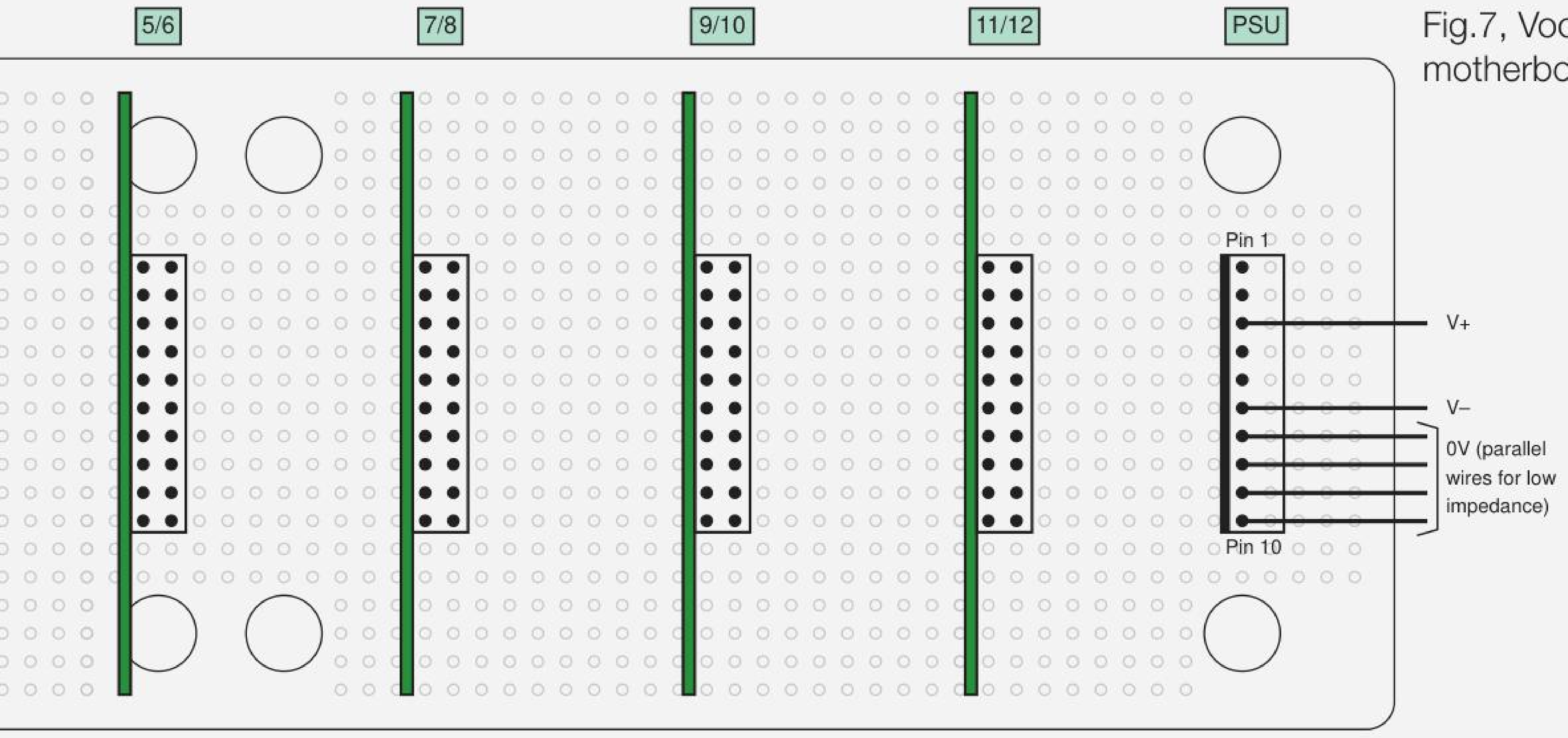

5/6
7/8
9/10
11/12
PSU
Pin 1
V+
V–
0V (parallel wires for low impedance)
Pin 10

Fig.7, Vocoder motherboard layout

with a few changes to heatsink-mounting holes. It supersedes the image in Fig.11 in last month’s column. Fig.3 shows the load-test resistors connected. Fig.4 shows tape fitted to insulate track under the heatsink. Fig.5 shows a PCB mounting hole that is just a little too close to the heatsink – just file away some of the heatsink above the PCB to allow the fixing to sit properly.

Motherboard

I have used a motherboard (Fig.6 and Fig.7) to bring the assorted *Vocoder* sub-systems together. All the filter boards are connected in parallel on the motherboard, which is essentially a bespoke stripboard. Seven straight double-row sockets (Rapid 22-5140) are inserted for the filter boards. Take care to insert the filter cards the right way.

On the left (looking at the motherboard component side) is a 10-way Molex connector for the audio signals, the two inputs and the left/right stereo outputs. These should be connected via screened cable. The screen being connected to the 0V pins of the signal Molex.

Power for the motherboard is supplied via another 10-way Molex on the opposite (right) end of the motherboard. Note that multiple 0V connections should be used to achieve the lowest possible ground impedance.

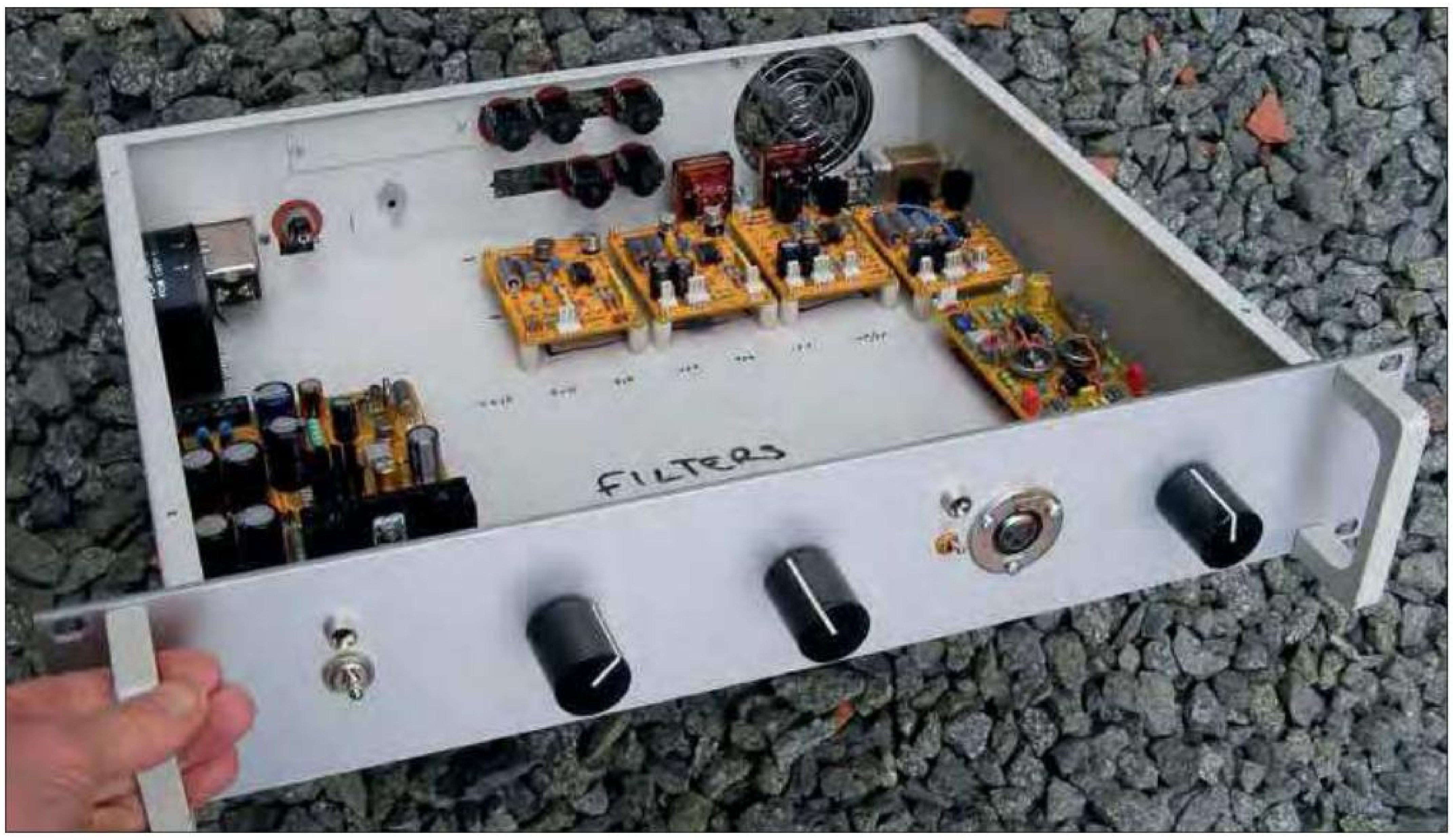


Fig.9. 19-inch rack case – expensive to buy new, but do look for second-hand bargains.

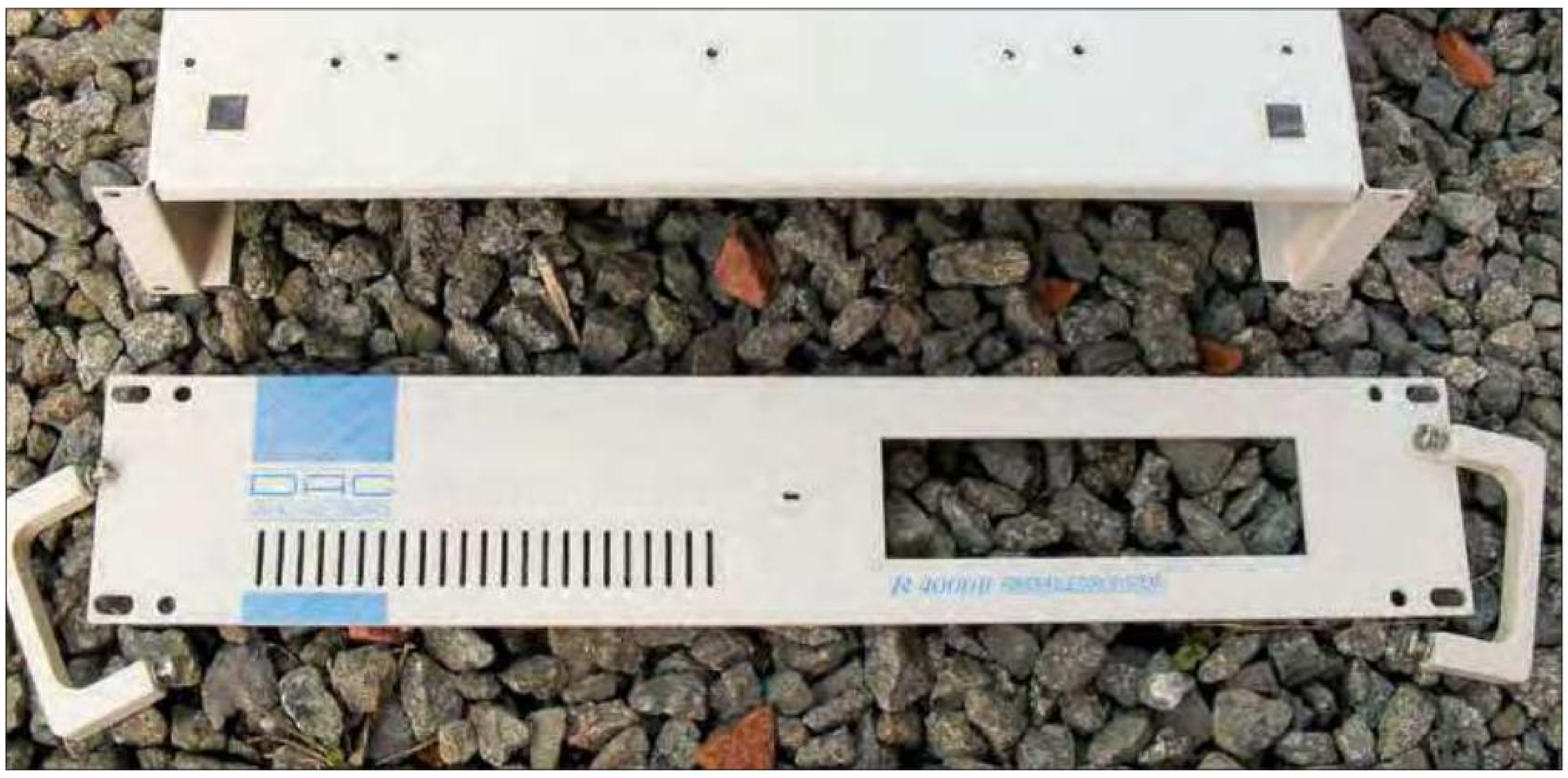


Fig.10. Reusing an old hard drive case (it was 44Mb and £400 in the old days).

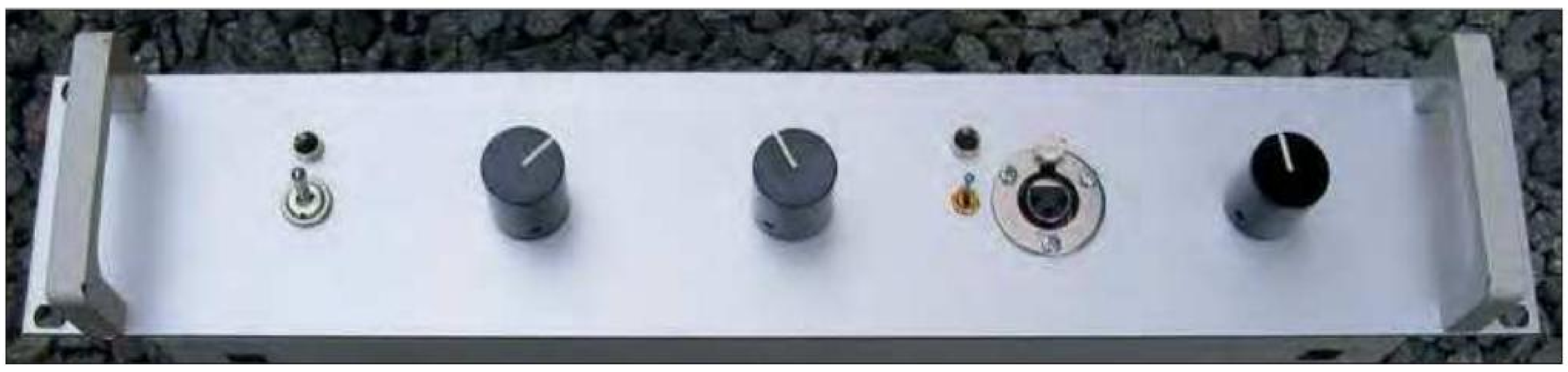


Fig.11. Front panel layout (left-to-right control knobs: synth/carrier direct level; modulator/mic direct level and mic gain.)

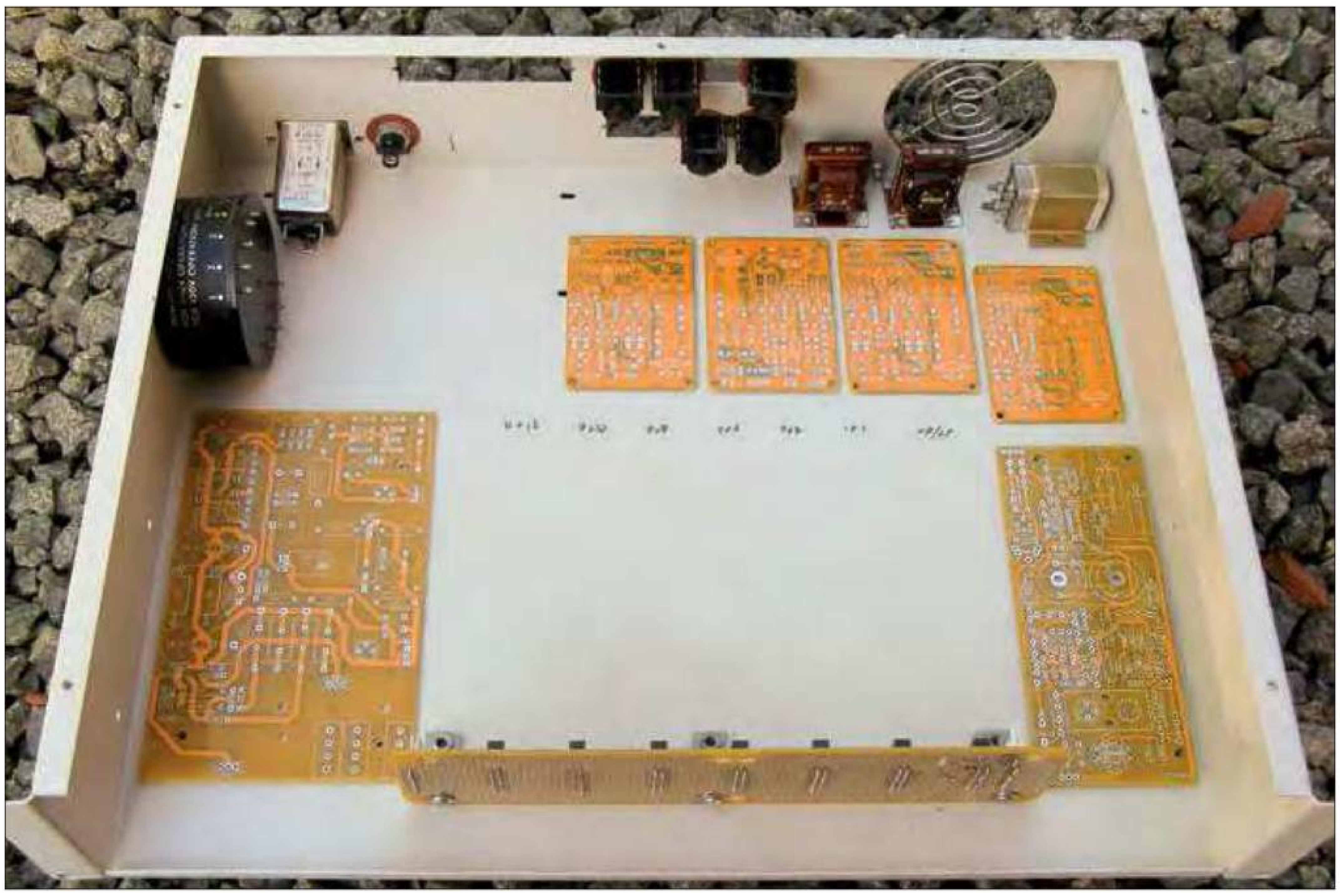


Fig.12. Enclosure ready for drilling.

The audio signals are connected to four driver boards (two input and two output). The output boards are configured as virtual-earth summing boards, while the input driver boards are configured for a balanced input. (See *Audio Out*, January and February 2022 on how to do this).

Optional inputs for direct synth and mic can be fed into the output mixing busses on the motherboard by using a 3-pin Molex connector. There is a stereo left/right input and a mono input. It is necessary to insert the four mixing resistors of 2.2kΩ shown. To avoid noise pick-up it's a good idea to break the three tracks to the right of the resistors. This can be seen in Fig.8 The motherboard uses plated-through holes so both sides have to be cut.

The direct synch and direct mic levels feeding these resistors are set by the 22kΩ linear pots, VR1 and VR2.

Vocoder block diagram

Fig.6 shows how the multiple sub-system boards are connected together to form a fully functioning *Vocoder*. See the note (top-right) about which parts are optional, extra features that can be added now or later. To fully use a *Vocoder* it is often necessary to mix its output with other signals. In the recording studio this is usually accomplished with a mixing desk and its computer-based equivalents. In such a studio situation only a basic *Vocoder* structure is required. This will have a carrier (or synth) input and a modulator (mic) input. There will also be the stereo outputs. All these connections will be balanced to wire up to a patch-bay where the *Vocoder* can be connected in any configuration with other studio equipment.

For a stand-alone *Vocoder* with an integral microphone preamplifier a bit of internal mixing is required. Since we already have a couple of mixing/summing amplifiers in the *Vocoder* it is a simple matter to mix direct mic and stereo synth signals into the output. Doing this makes the sound clearer and thus performance easier.

'Just-in-case' junkies

When I was a young constructor, I had a junk box. To my wife's horror I now have three junk rooms. On a square footage basis, these rooms are worth around £100,000, so I suppose I ought to start using up some of the £5000 worth of junk stored within. I've started the decluttering process by using an old hard drive 2U 19-inch rack case for the *Vocoder*, as shown in Fig.9. If you can't find an old case, you might have to cough up £82.20 for a new one, such as the RS 801-434 from Schroff (but you'd probably get a

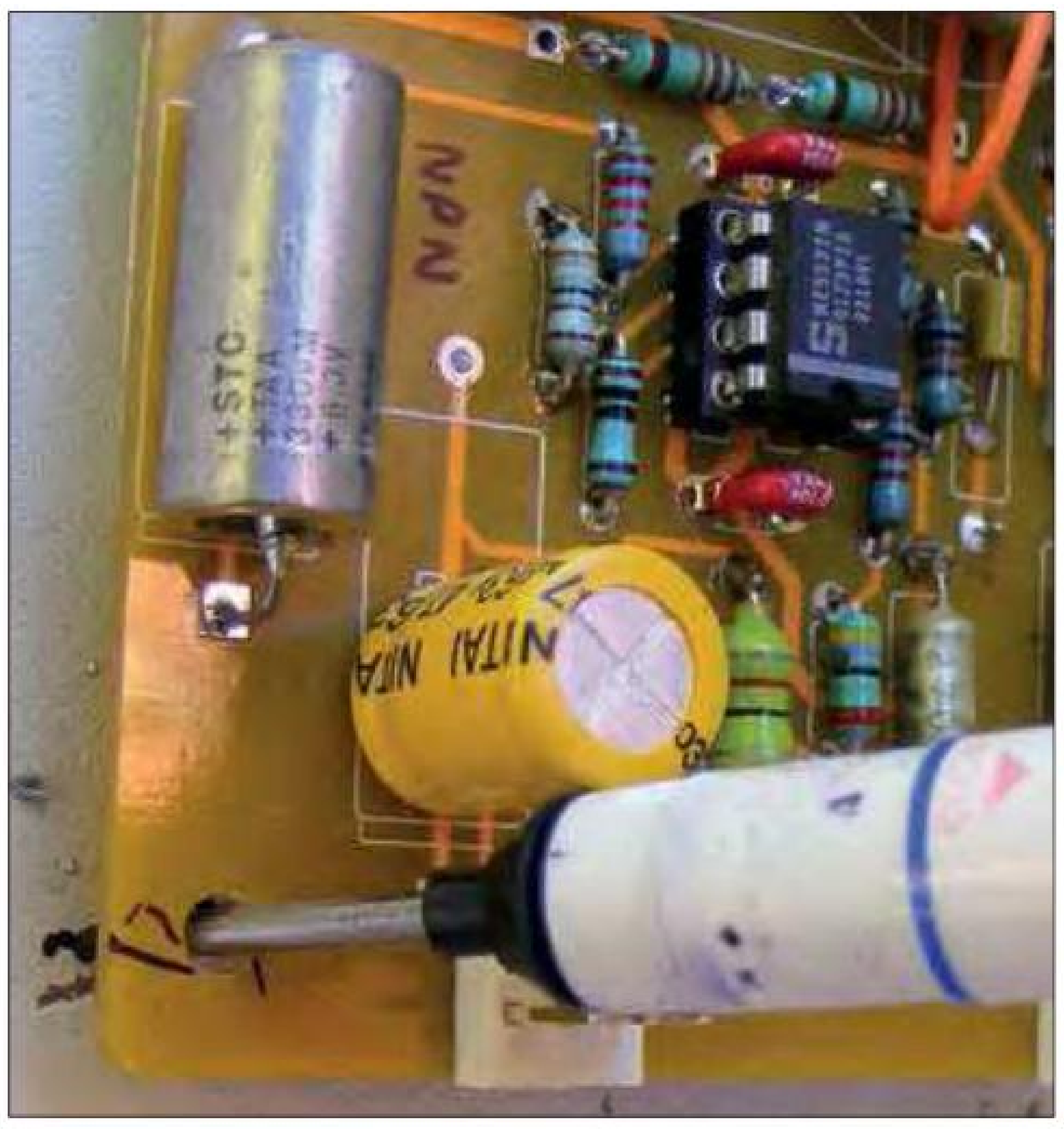


Fig.13. A carpenter's pen is ideal for poking through board mounting holes for marking drill holes.

Fig.14. (Top) Drill 'wandering' is avoided by centre punching. Fig.15. (Bottom) Automatic centre punch – a worthwhile investment for drilling holes.

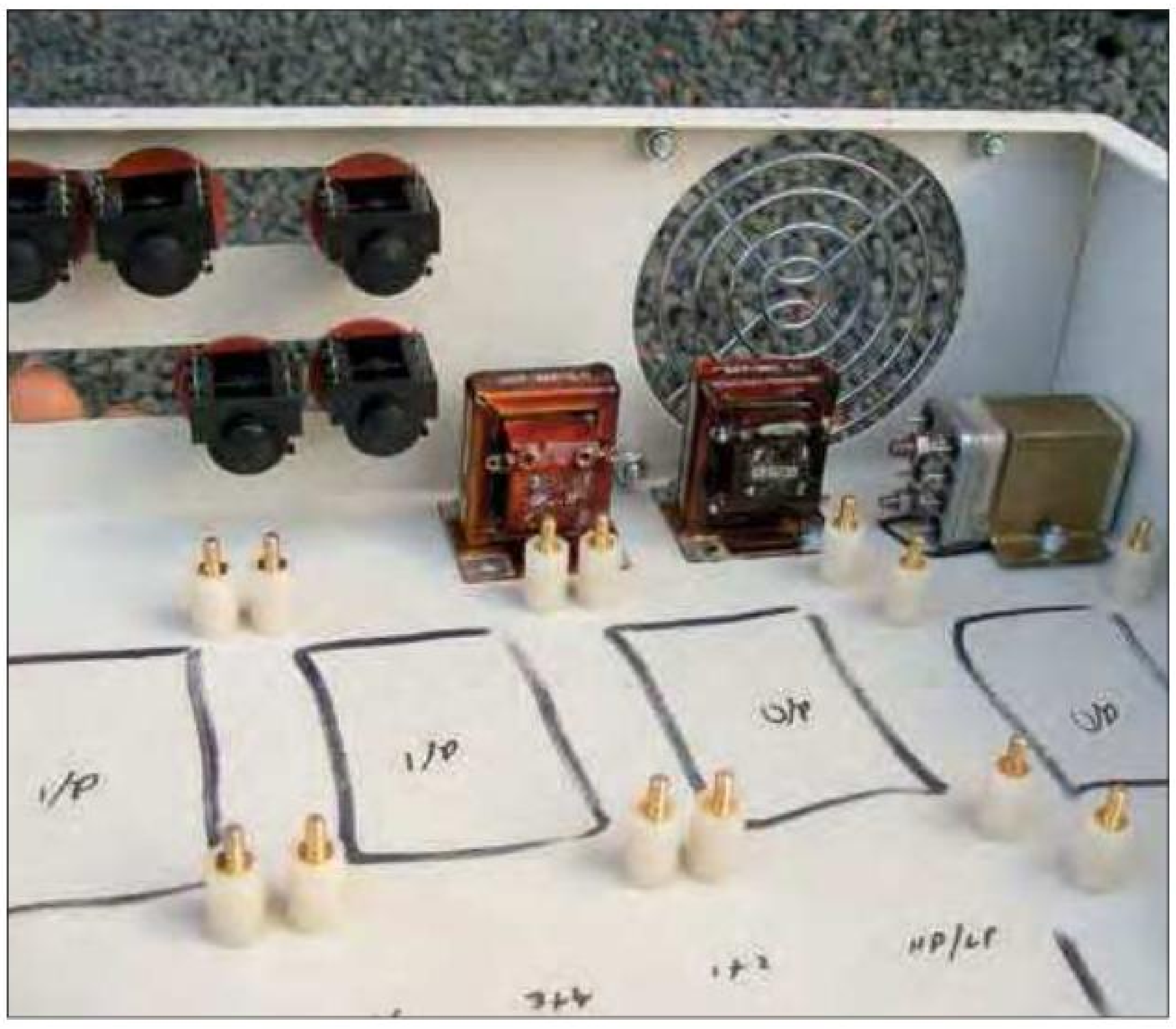


Fig.16. Nylon brass-insert spacers are ideal for PCB mounting. Stick-down ones don't stay stuck!

much cheaper one on eBay). I did have to buy a new front panel (Hammond PBPA19003GY2, Rapid 30-7201) because of the disfiguring slots and awful 1980s graphics (Fig.10). I was able to reuse the metal handles though, which also act as knob protectors. If you don't fancy eBay, a great many older electronics constructors are downsizing to bungalows – so now's the time to pick up 19-inch rack gear from radio rallies for a tenner!

The 19-inch standard might be regarded as excessively large for today's constructor, but in the 1950s it was perfect for valve equipment. It is still the standard today for analogue recording studio gear and lab instrumentation. The large size is beneficial for development work since many modifications can be easily incorporated and this *Vocoder* design is a long way from being a small surface-mount device, plastic-cased commercial product!

Layout

The mic input and the mains transformer should be as far apart as possible to minimise hum. This normally means they're placed in opposite corners. Also, the lowest-frequency filter cards should be the furthest away from the transformer. I had to put the mains wiring on the left-hand side of the box because the hole for the IEC mains connector was already there. (If there's one thing I hate in electronic construction it is cutting rectangular holes in steel panels. It's a quick way to A&E if you don't have the right tools.)

Front-panel design

A whole article could be written on this aspect of audio (and one day I will). Normally, I like the signal flow to be from left to right, but in this case, due to the position of the mains wiring I had to put the input socket on the right. There is no general standard for power-switch positioning, but in audio it's always 'down for on', the opposite to normal electronic practice. This is because it's unforgivable to accidentality turn something off and end up with 'dead-air' in broadcasting. The basic layout is shown in Fig.11.

Drilling

Once the subsystem layout for your particular box has been finalised, usually after 30 minutes of shuffling things around (Fig.12), it's time for the lovely job of drilling mounting holes. First, these have to be marked out by positioning the boards and poking through the mounting holes with a long-nibbed felt pen. The Edding 8850 carpenter pen is ideal for this job (Fig.13). The next job is to centre-punch each hole to stop the drill wandering (Fig.14). If you are stuck, a hammer and nail will do the job, but if you are going to do a lot of metal-bashing it's wise to invest in an automatic punch (Fig.15) where a spring delivers a defined blow as it is depressed. If you aspire to high quality audio, remember to protect your most important asset while doing this kind of high-impact noise-generating work – wear ear protectors.

Usually, PCBs are mounted with M3 screws and spacers. I also like nylon brass-insert spacers (RS PRO 601-136, see Fig.16). At £1.60 each, they're expensive, but they have a little 'give' in them to accommodate slight drilling tolerances. A 3mm 'jobber' high-speed steel (HSS) bit is used to drill the holes. Sometimes it's not impossible to drill holes located near the corners from the inside of an enclosure; just turn the box over and drill from underneath.

I pilot drill all holes at 3mm and then work up to larger holes – for example, 4-5mm for toroidal transformers and 12.5mm for jack sockets. Bigger holes, such as for XLR and IEC sockets are best done with dedicated hole cutters supplied by 'Q' Max and RS. However, these are expensive and the hand-operated ones require considerable strength, but 'chain drilling' with small drill bits and finishing with a file also works.

It's a good idea to chamfer all small holes with a larger 10mm drill bit (Fig.17). For large holes and apertures, a round file or proper de-burring tool is required (Fig.18). Remember, always clean up all swarf after metal work with a brush and big magnet. If these particles enter the magnetic systems of loudspeakers, microphones or motors, they can ruin them!

The main *Vocoder* filter card assembly is mounted with angle brackets (Fig.19). PCB guide slots are needed to stop the filter cards wobbling about. I had none, so I used red felt strip from an old loudspeaker as a stop-gap. A spring-loaded clamp to hold them all down is also recommended for on-the-road use. Another useful

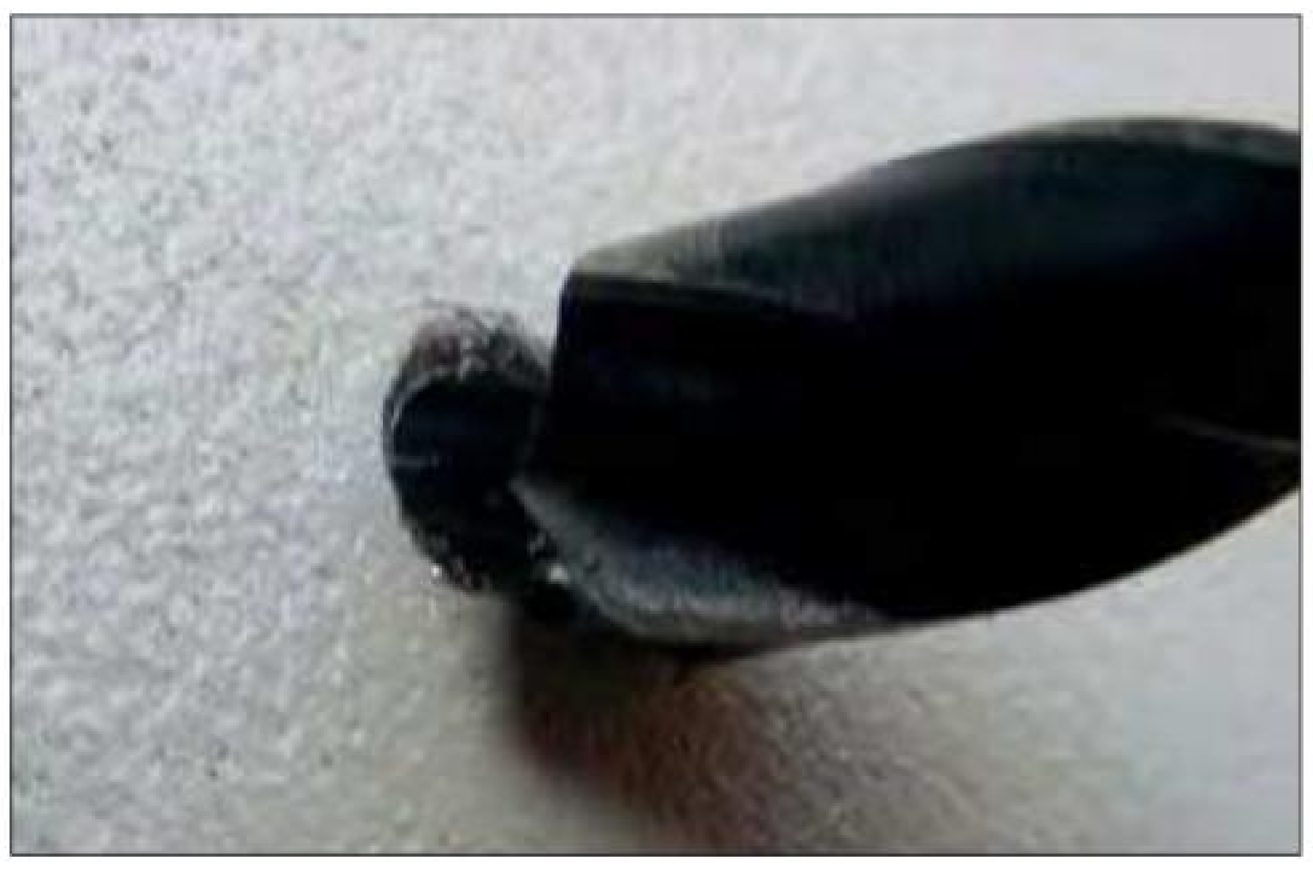


Fig.17. Small holes can be deburred with a larger diameter twist drill.

Fig.18. Use of proper de-burring tool for large holes.

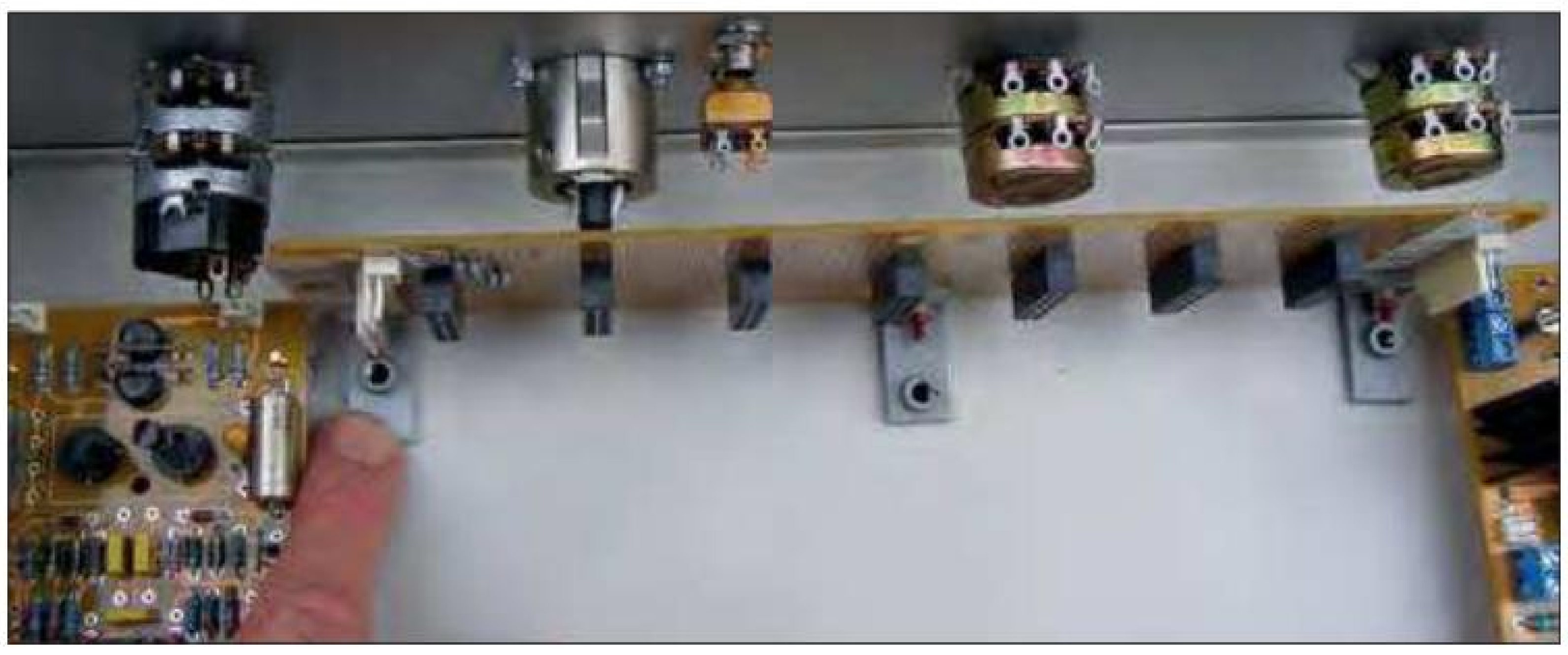


Fig.19. Mounting the motherboard with angle brackets.

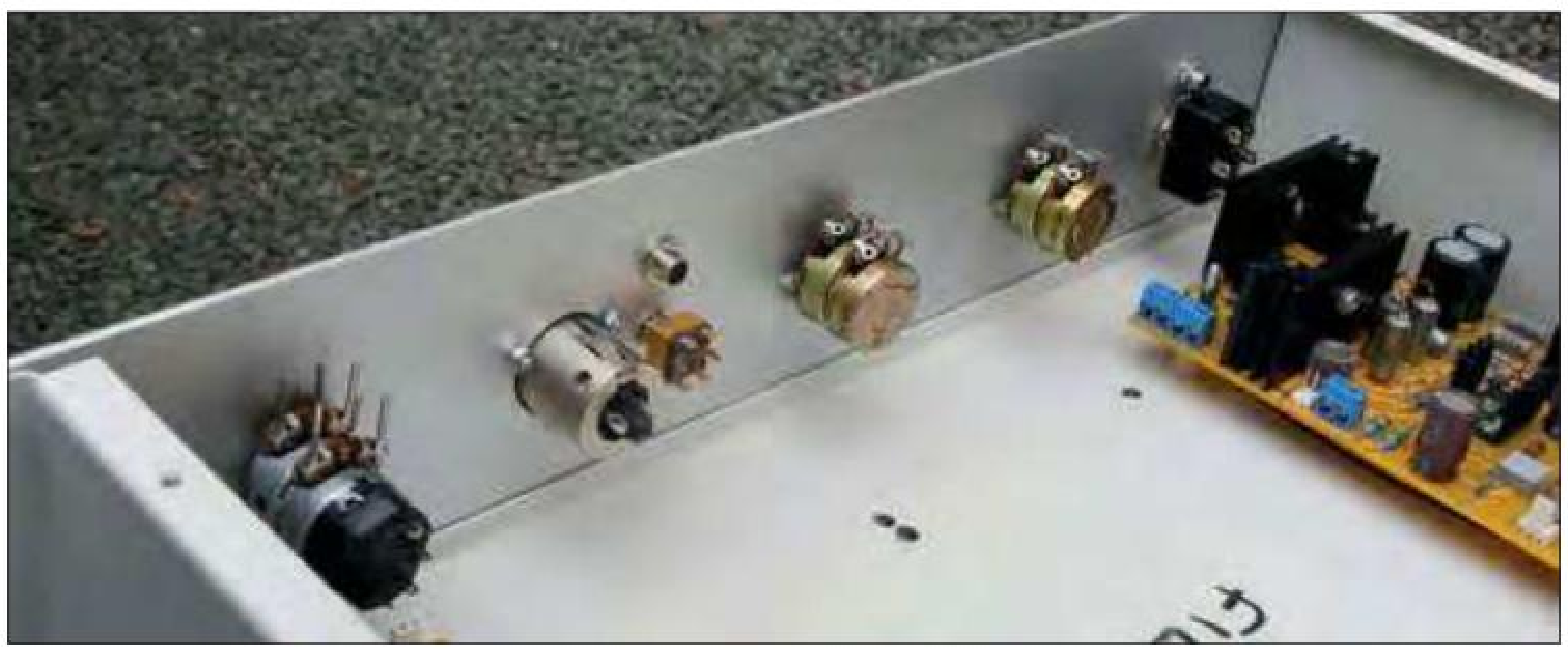


Fig.21. Front panel components rear view.

anti-vibration measure is to use spring or shakeproof washers under all the screw heads. I like to use a 6mm-long bolt with an integral lock washer, such as RS 278-641 to mount the spacers (Fig.20). The front panel components are shown in Fig.21.

Mains wiring

In commercial equipment it is now a legal requirement to use a double-pole mains switch, which switches both mains conductors (live and neutral) rather than just the live. This is because residual current devices (RCDs) in buildings can be tripped by an earth-to-neutral leakage current as well as the more important live-to-earth short. The last thing you want in a studio is sudden power loss. (There is also the possibility some incompetent DIYer has wired up a mains lead backwards.)

The IEC socket should be of the filtered variety, and it is also good practice to follow this with a transient suppressor or voltage-dependent resistor (VDR), often called a 'varistor'. The best place to put the VDR is right on the transformer's primary winding, as shown in Fig.22. A suitable device should have a 250V AC rating and a peak energy dissipation of over 100J (joules), such as the Epcos B72220S0251K101 (Rapid order code 51-4590). Generally, the bigger it is, the more energy can be absorbed, this Epcos device is 20mm in diameter.

Earthing

The safety of any metal equipment enclosure is dependent on the integrity of its earthing. To be legal, it is essential the mains earth has a resistance of <0.2Ω between the earth pin of the plug and the metalwork. I use a 'star-tag' with a solid M4 fastening with shakeproof washers on all surfaces. Remember to scrape off any paint or anodising, as shown in Fig.23. Remember that these earthing requirements also apply to the front-panel mounting arrangements.

Fuse holders and sockets

I'm sure many an older electronic boffin has had a shock undoing a fuse on a back panel. This can be avoided by wiring it the correct way, with the end tip going to the live input and the tag nearest the rear panel connected to the transformer. The fuse should also be after the mains switch, as shown in Fig.24. Alternatively, an IEC socket with a built-in fuse holder reduces wiring. Make sure all mains wiring is properly insulated with rubber boots and sleeving (Fig.25).

Balanced connections

A female XLR is used for the balanced microphone input since this is the standard. The line level input and output connections are jack sockets, commonly referred to as 'tip, ring, sleeve' or 'TRS jacks' in audio circles. These connectors have the advantage of being able to accept unbalanced (or mono jacks) as well as balanced. This is useful, since most synthesiser outputs are unbalanced. A benefit in construction is that the 12.5mm mounting holes are much easier to drill than XLRs. This was a major advantage with the hard steel case used. I didn't even have to drill these. I mounted the jacks in the old 'D' connector slots using M12 fibre washers (Fig.26). The aluminium front panel made drilling the XLR hole relatively easy. I used a standard 25mm serrated hole-cutter, as shown in Fig.27.

Muting relay

Extraneous powering up/down noises can ruin recordings and ears, so the outputs of the unit are muted until the circuitry has settled. This is best done with a relay. The change-over contacts are used to ground the output transformer winding when the unit is off, and to connect to the audio outputs when on. We don't want the transformer to act like a hum pick-up coil. Unfortunately, the relay originally used in this *Vocoder* was discontinued long ago and to compound the situation I found most of my stock in the '24V relay drawer' turned out to have 48V coils. These are much better employed in power-amps for speaker muting. Instead, I have opted to use a much smaller signal relay, the gold-plated contact Hongfa HF-D2/024-S-D (Rapid order code 71-4713). This is small enough to be mounted on strip board (Fig.28) and will happily fit into a 16-pin turned-pin DIL socket.

Output transformers

Low harmonic distortion is not required for musical instruments and the 'soft' distortion of iron-cored output transformers is regarded as 'musically enhancing'. Thus, the Hi-Fi distortion-cancelling circuitry on the driver boards is not needed for the *Vocoder*. In my circuit I used cheap output balancing transformers (New old stock (NOS) Gardeners surplus transformers – see Fig.29. I sell these from the AO Shop.)

For stability, do remember to take the earth return from the transformer directly

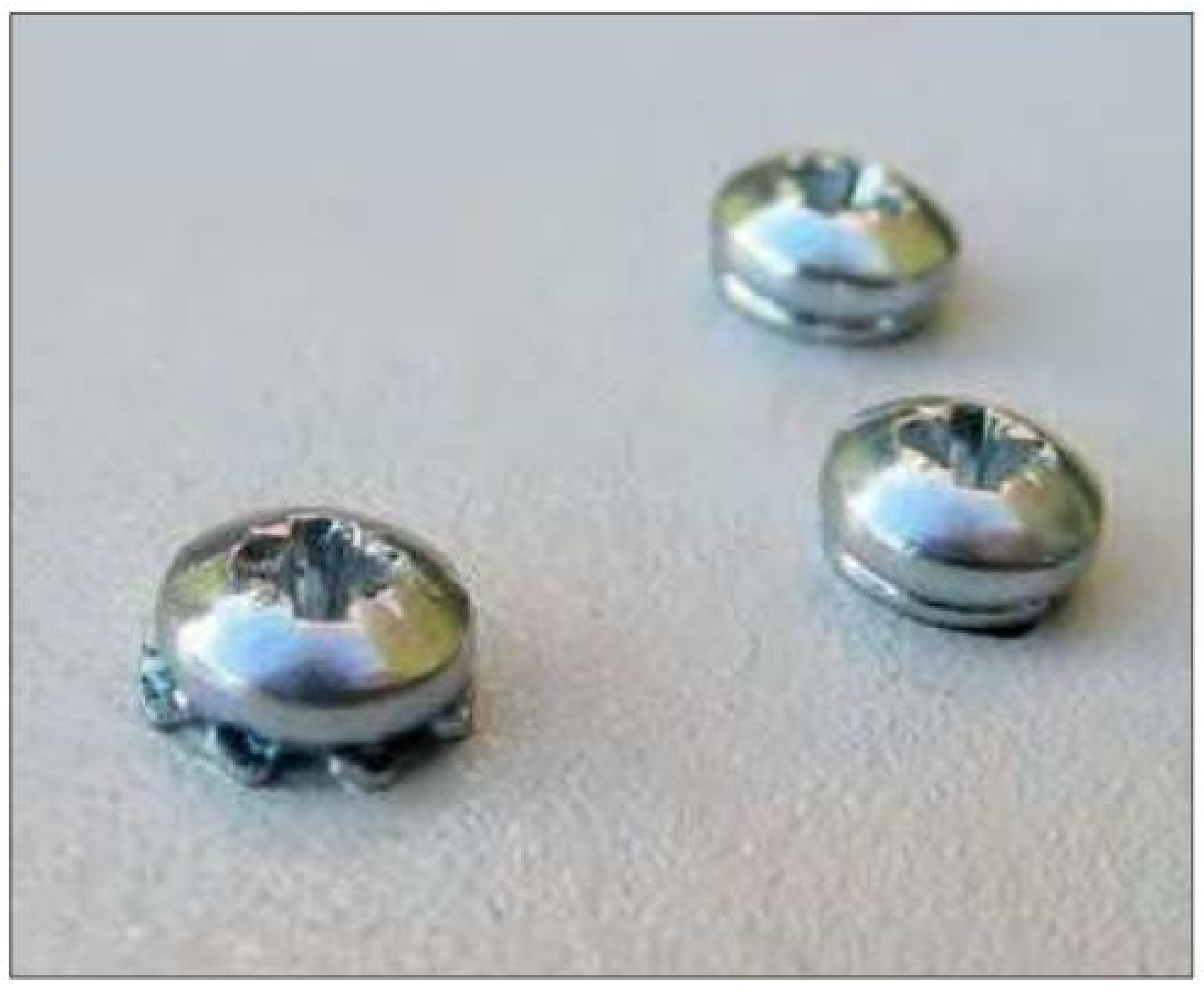


Fig.20. Bolts with integral lock washers are quicker to install and more secure.

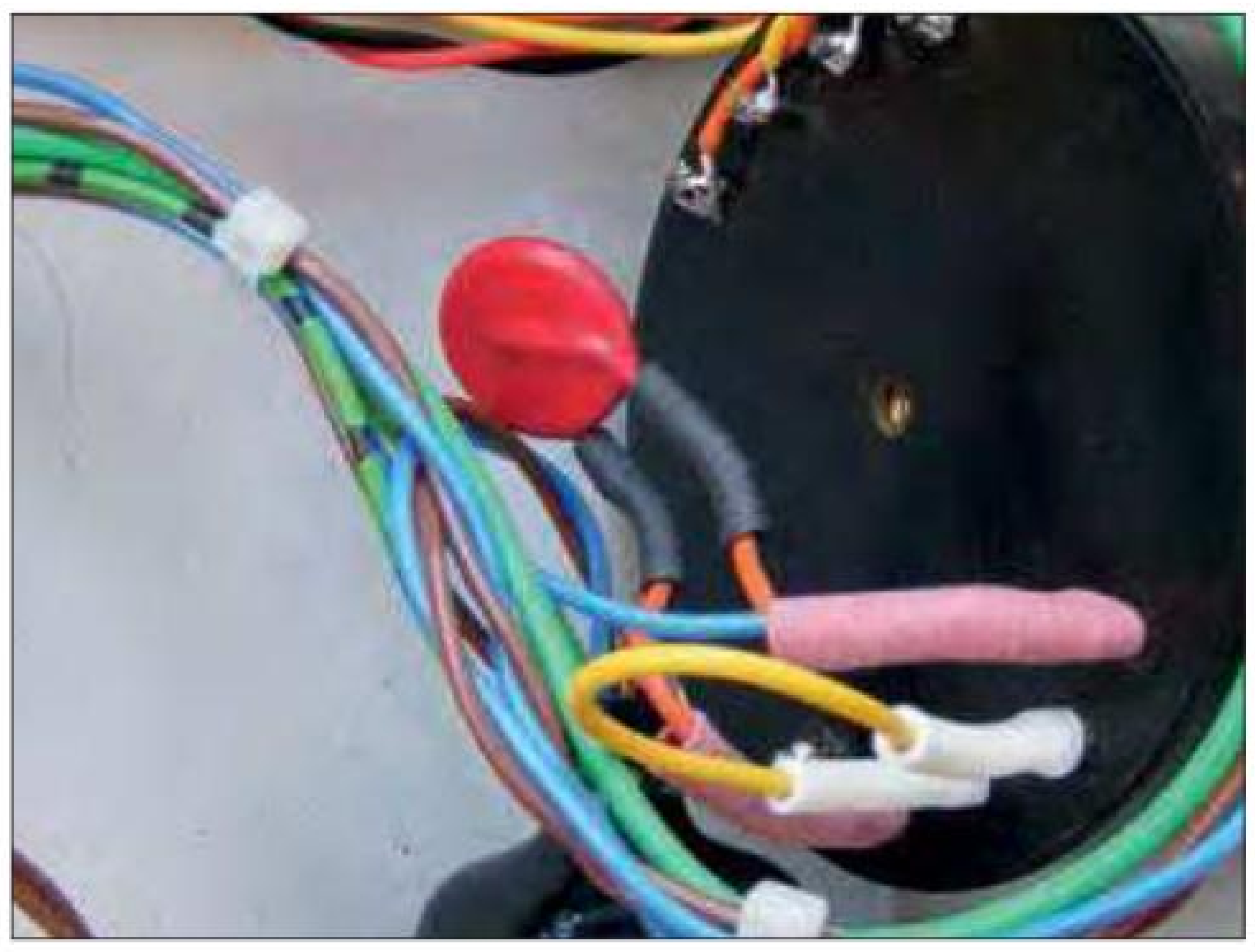


Fig.22. A zinc-oxide varistor is wired across the transformer primary to absorb mains transients.

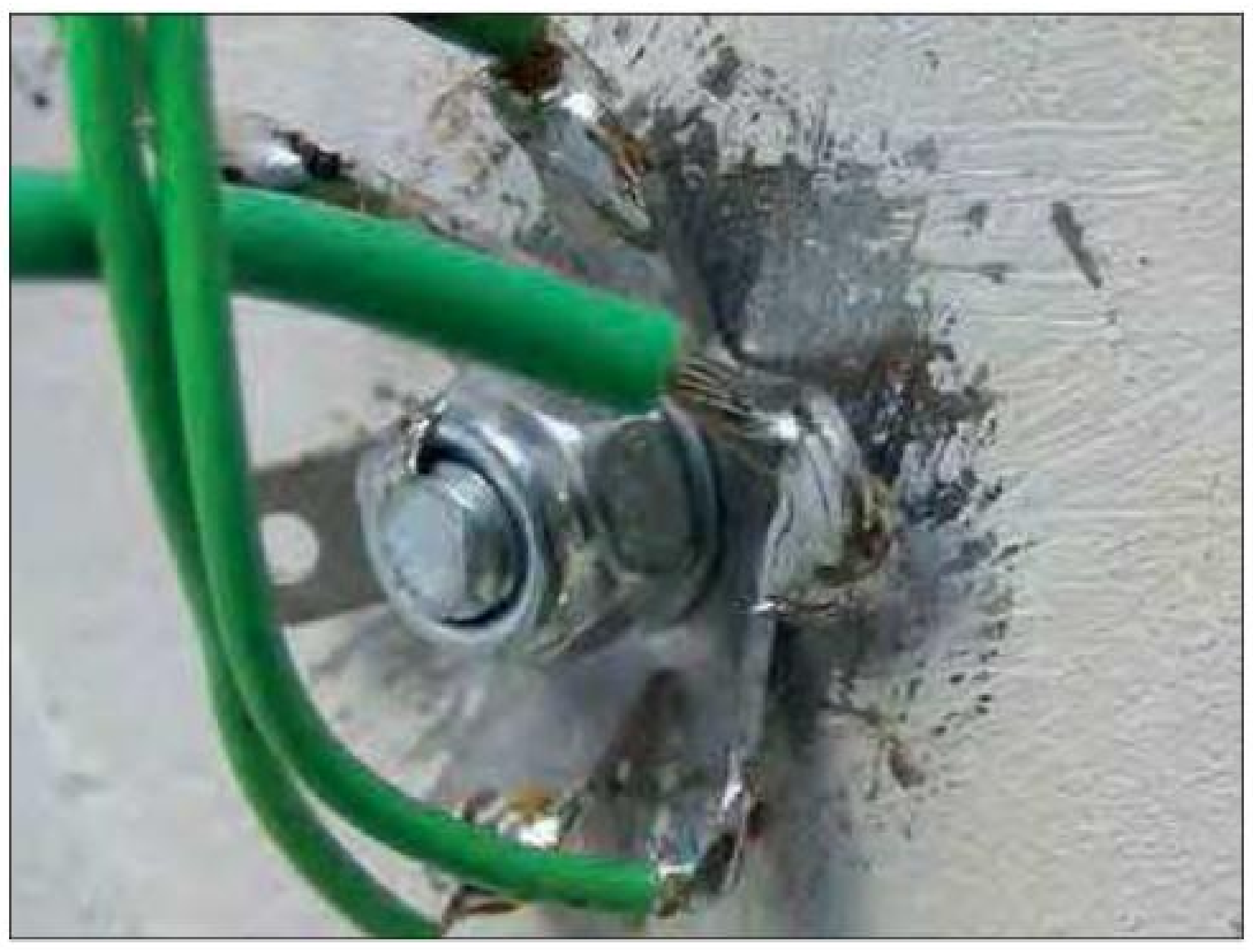


Fig.23. Main earthing stud for a metal box. Note how the paint has been removed to obtain good contact.

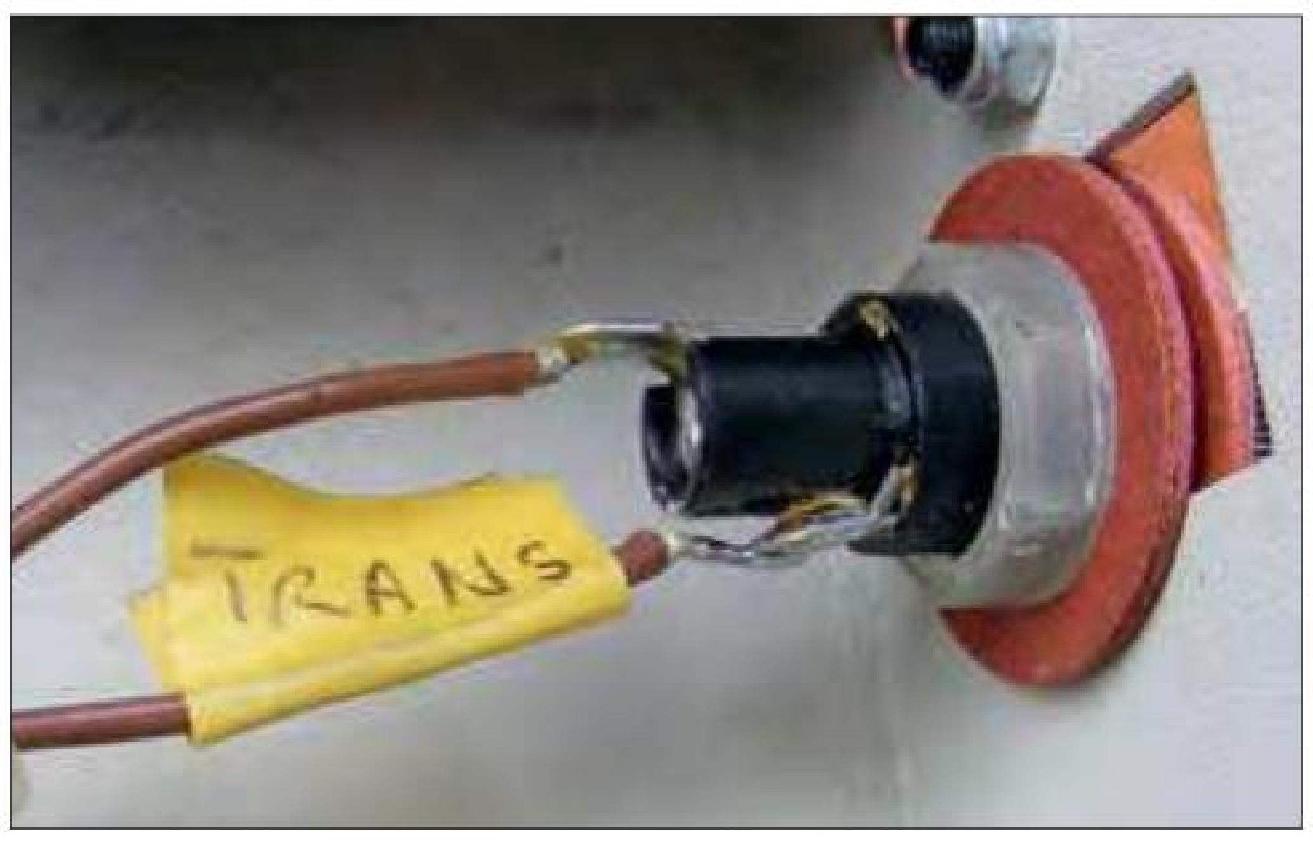


Fig.24. The fuse should come after the switch. The fuse here (315mA 20mm time-delay) protects the transformer. The mains wiring is protected by the 3A fuse in the mains plug.

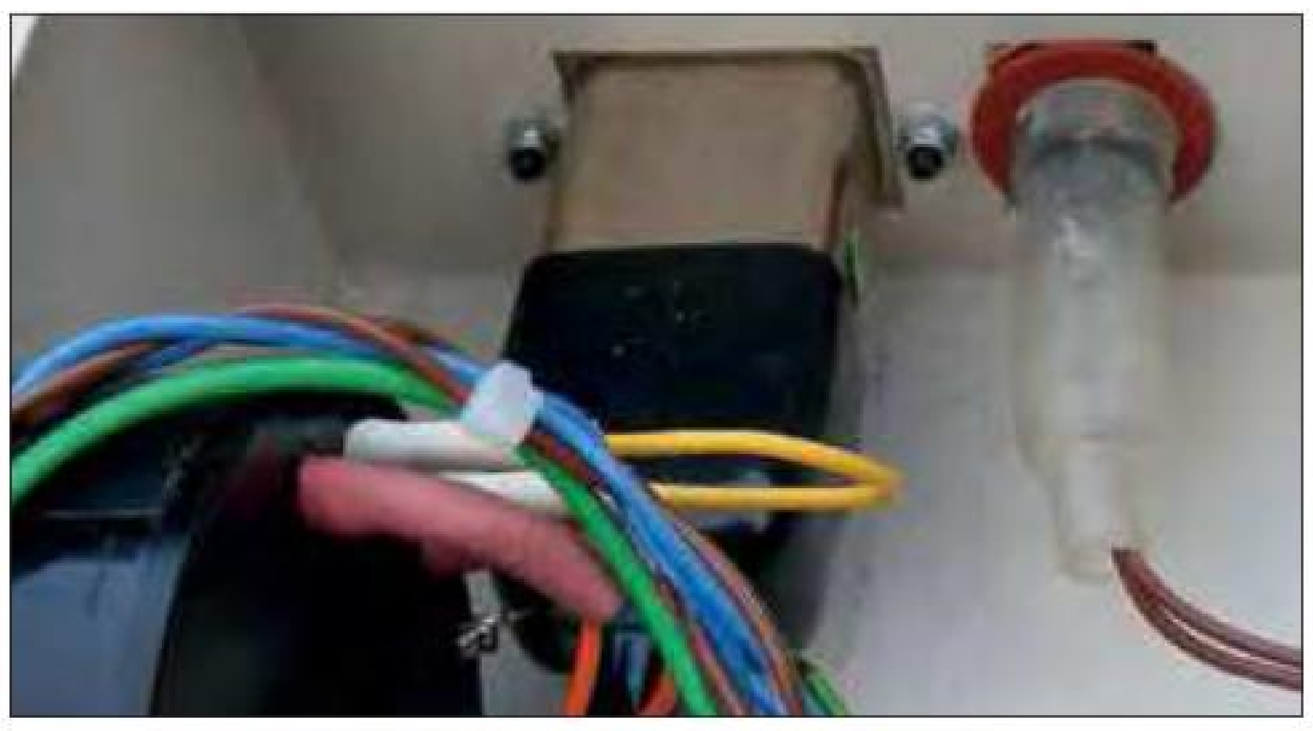


Fig.25. Mains wiring – note extensive insulation sleeves/boots to prevent shocks.

to the power supply's 0V. Alternatively, you can use any other 600Ω output balancing transformer, for example one from Vigortronix.

Wiring

With large systems like this, it's best to lay down the power supply and earthing first. Get that going properly, before doing the signal wiring. Since all the boards have pluggable power connectors, power can then be applied to the boards in easy testable steps. In a large multi-board project such as this, do not daisy-chain supplies; it's best to 'star' (bring to a central point) all the V+, V– and 0V connections to the power supply board to minimise interactions. These cables can be seen laced together going to the power supply.

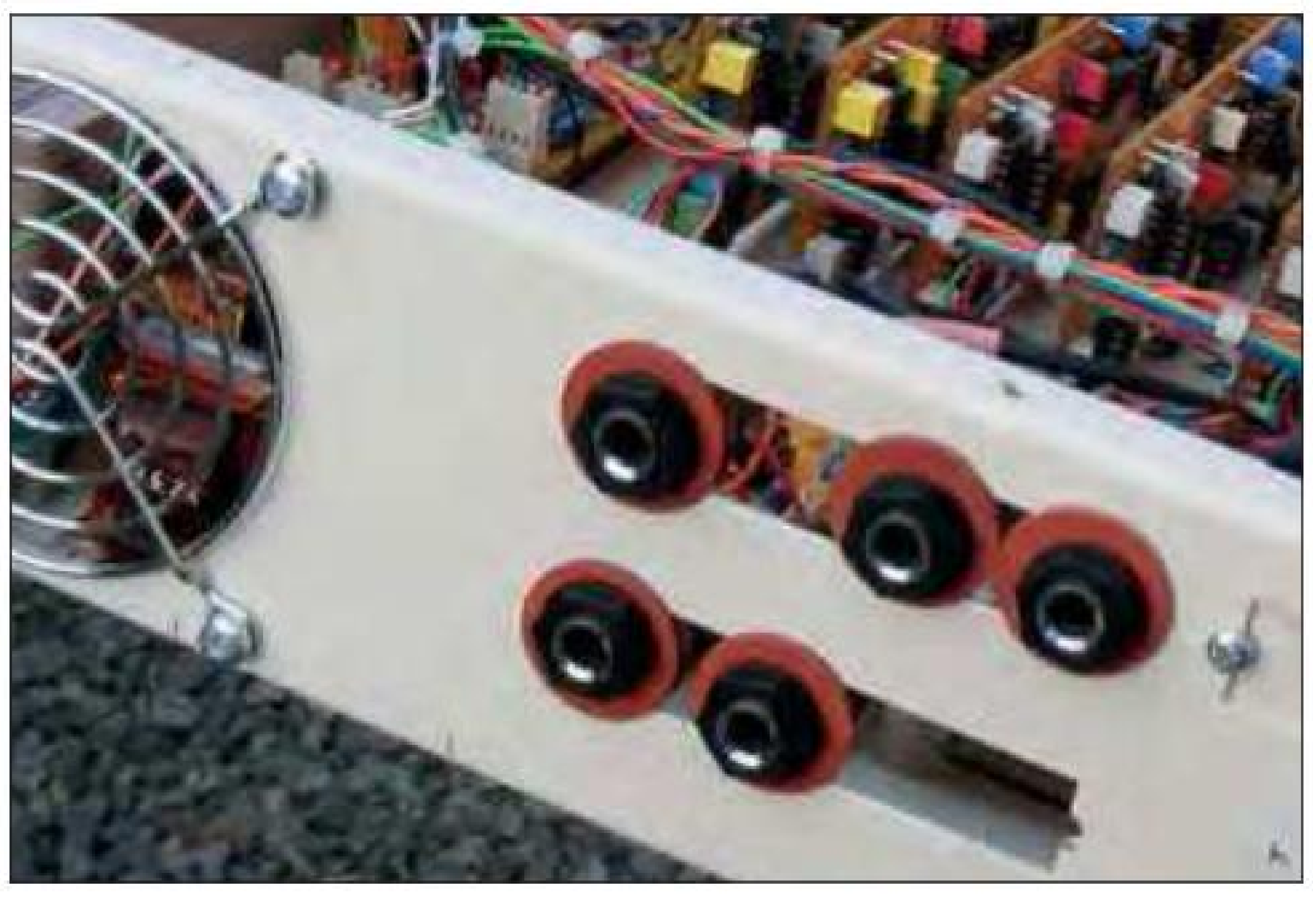


Fig.26. Jack sockets adapted to fit into ready cut slots with M12 fibre washers.

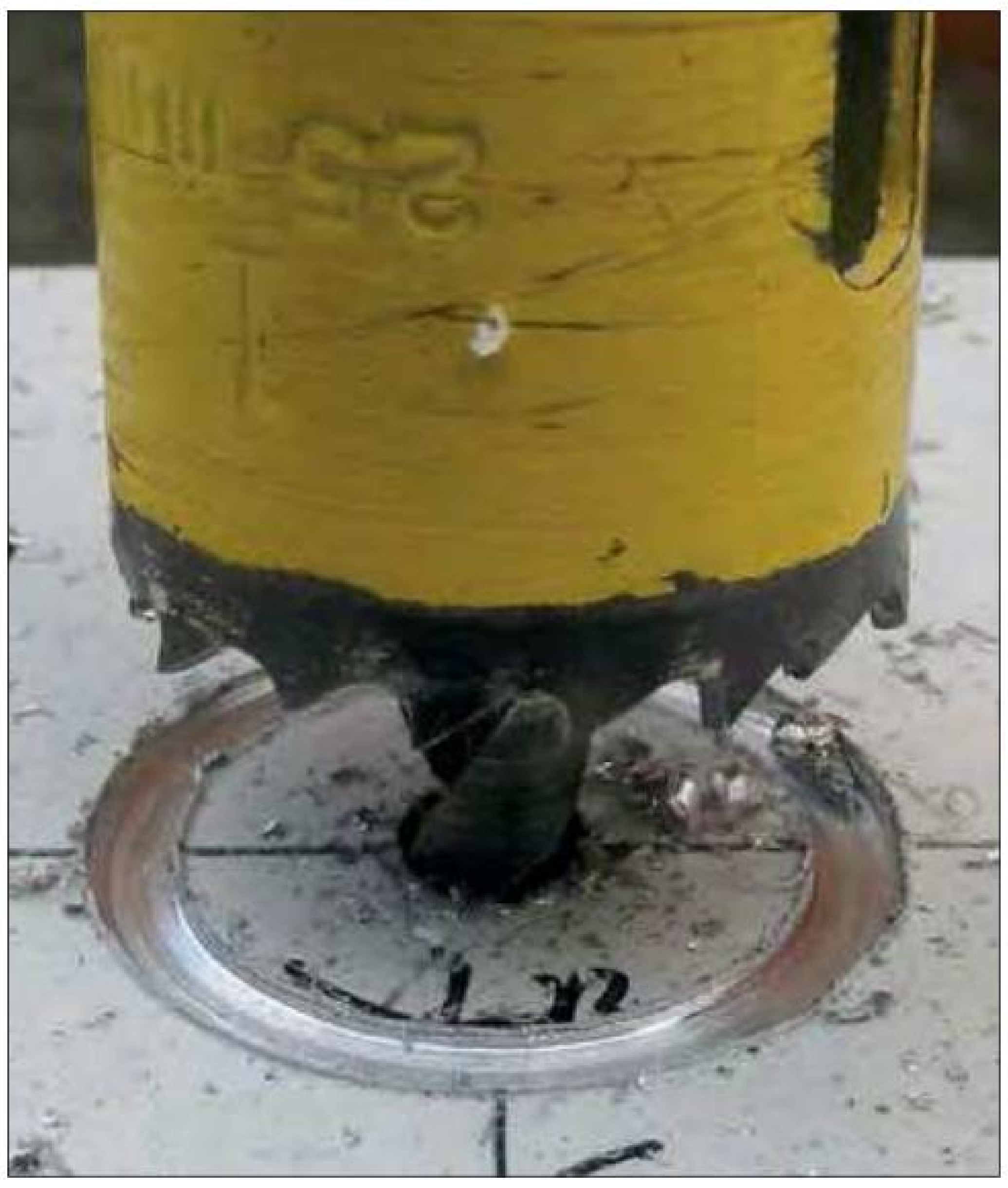


Fig.27. Cut large circular holes, such as those for XLR connectors, with a toothed hole-cutter.

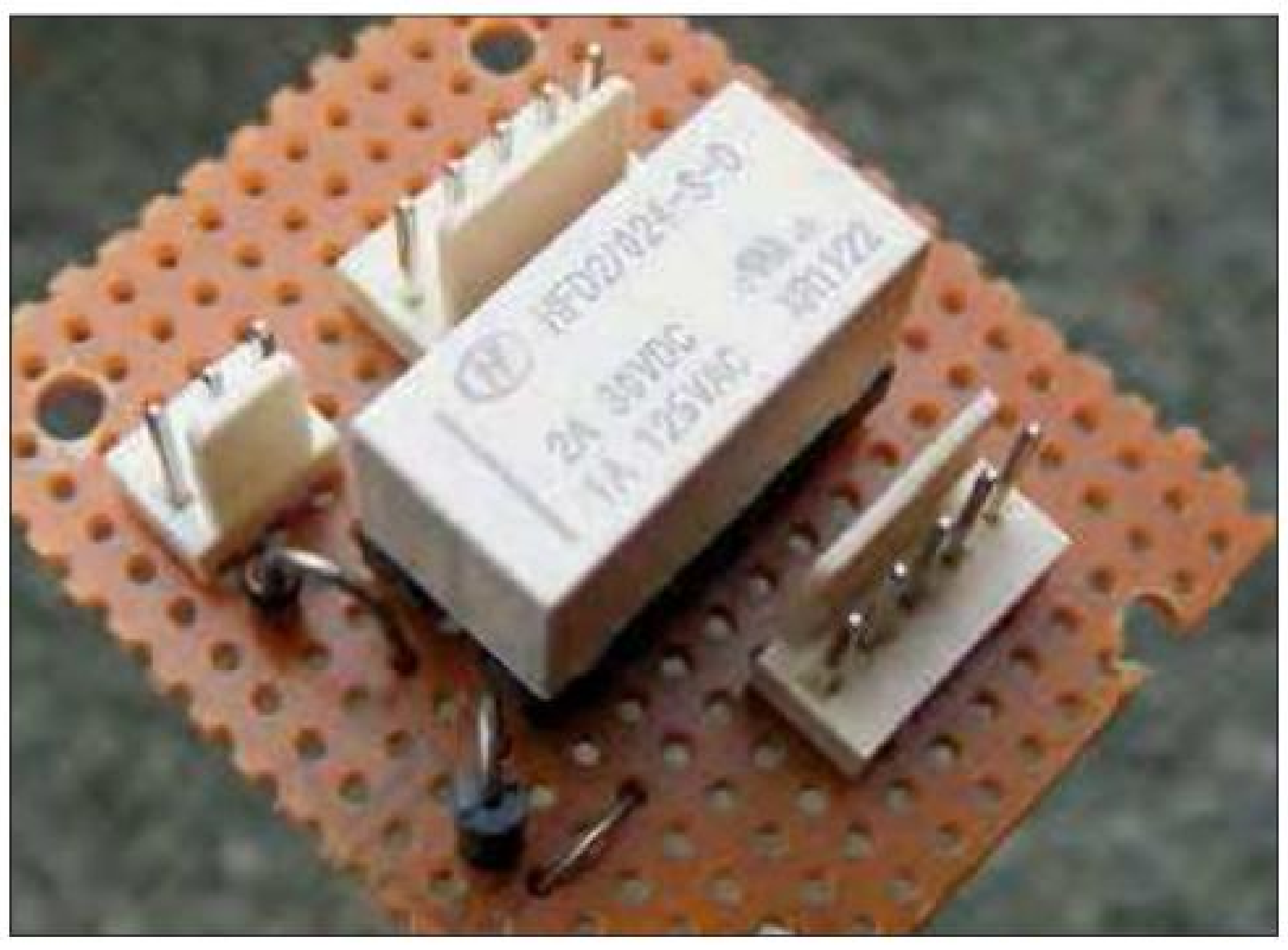


Fig.28. A good modern relay for muting.

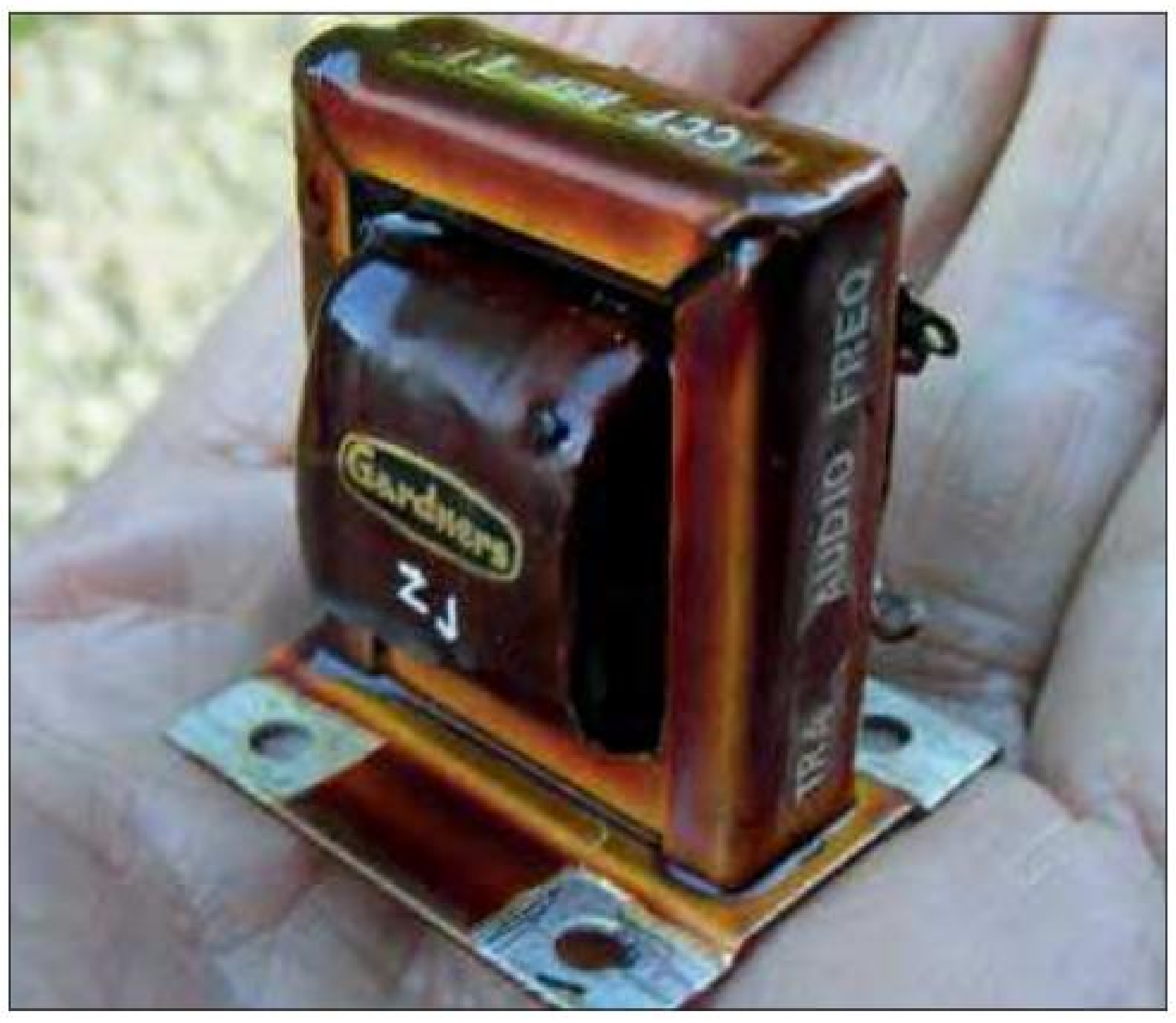


Fig.29. New-old-stock audio output balancing transformers (available from the AO Shop – see page 41).

For safety, don't lace mains wiring with low-voltage wiring. For lowest hum, keep all audio leads well away from the transformer or any AC wiring. All audio cables should be screened. Don't use the braided type since this is difficult to crimp to the connectors. Use Belden studio cable or similar with a twisted drain wire and foil screen. The earth connections on the balanced jacks all go to the chassis. The final wired unit is shown in Fig.30.

Testing

It is assumed at this stage that all boards have already been tested to avoid pulling the system down with power supply shorts, instability and other problems.

Shut the lid and make music

Vocoders are one of those pieces of electronic equipment that enable technicians to appear like musicians. Every 'Eurorack man' aspires to one since it enables them to move on from instrumental bleep and boop sequences. Feed the *Vocoder* with a piano soundtrack from a YouTube video of your favourite tune and just talk into the microphone and away you go. I did a good rendition of 10cc's 'I'm Not In Love' that way. Surprisingly, talking into a *Vocoder*, rather than singing the tune can give smoother results. This is because if the frequencies of carrier and modulator exactly coincide, nasty feedback-inducing peaks can occur. Have fun!

Sourcing PCBs

All the PCBs for the *PE Analogue Vocoder* are now available – see the May 2022 page of the *PE PCB Service*.

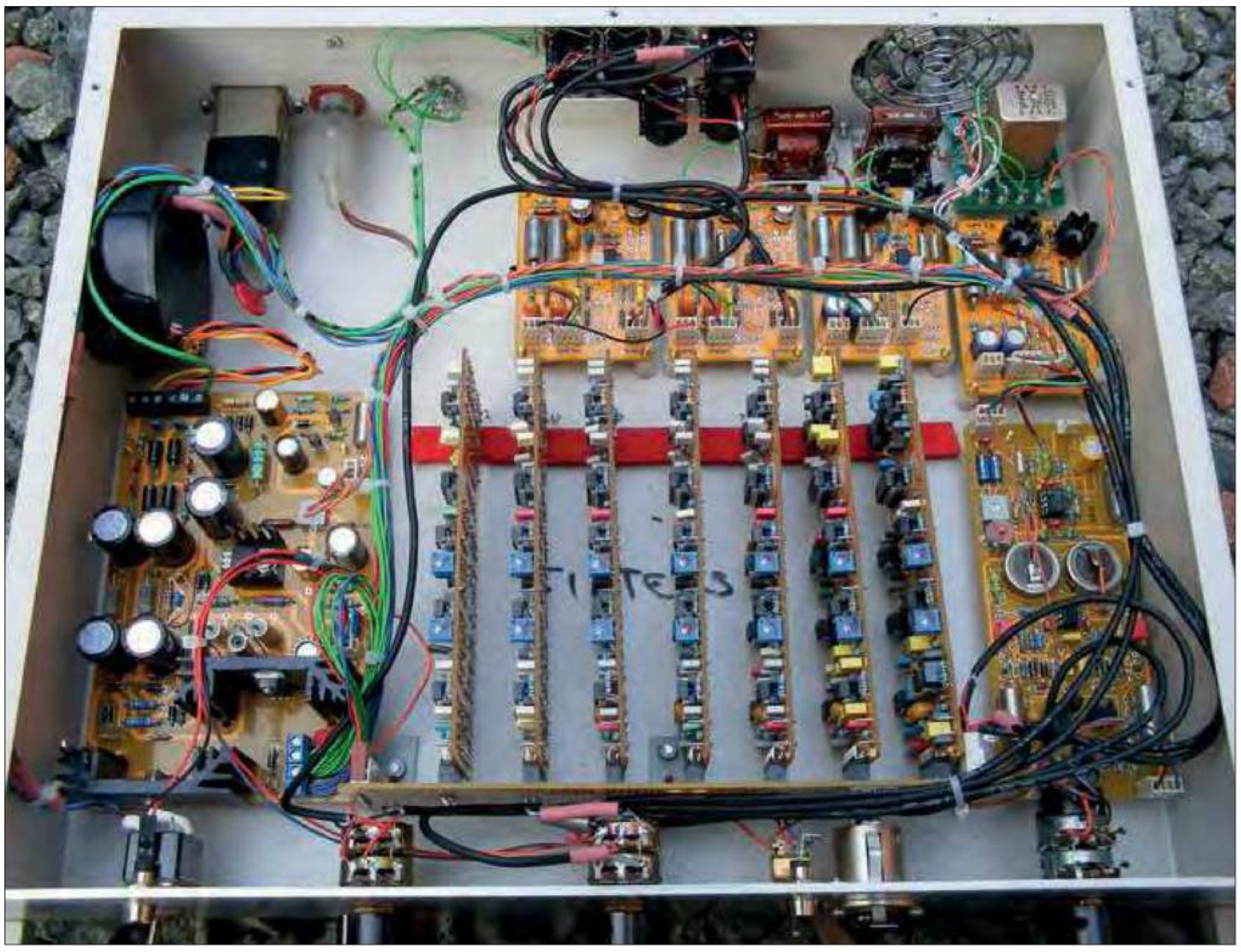


Fig.30. Completion of the Vocoder wiring.

Max's Cool Beans

By Max the Magnificent

Flashing LEDs and drooling engineers – Part 27

I don't know about you, but my days seem to be slip-sliding away under my nose ever faster. In addition to my day job as a freelance technical consultant and writer ('I'll write for food'), I'm typically to be found juggling a plethora of projects on the hobby front. I'm also constantly being bedazzled and beguiled by the scintillating selection of 'stuff' that I randomly run across as I meander (some may say 'blunder') my way around the internet. To top things off, I also have a short attention span and I rarely get to finish anything before something new and shiny comes along to distract m... SQUIRREL!

Print your own

It's not so long ago that electronic hobbyists had to capture circuit schematics by hand and etch their printed circuit boards (PCBs) using noxious chemical compounds under exile in the bowels of the basement. These days, by comparison, there are a variety of affordable design tools available that allow hobbyists to capture schematic diagrams and create corresponding PCB layouts. Even free tools like *DesignSpark* PCB (**https://bit.ly/3pBQuWE**) are incredibly powerful and sophisticated. In many cases, these tools have capabilities that were the stuff of dreams for high-end professional offerings just a few short years ago. And, once you've captured your PCB layout, there are numerous fabrication facilities clamoring to create affordable prototypes and deliver them into your eager hands in a timely manner.

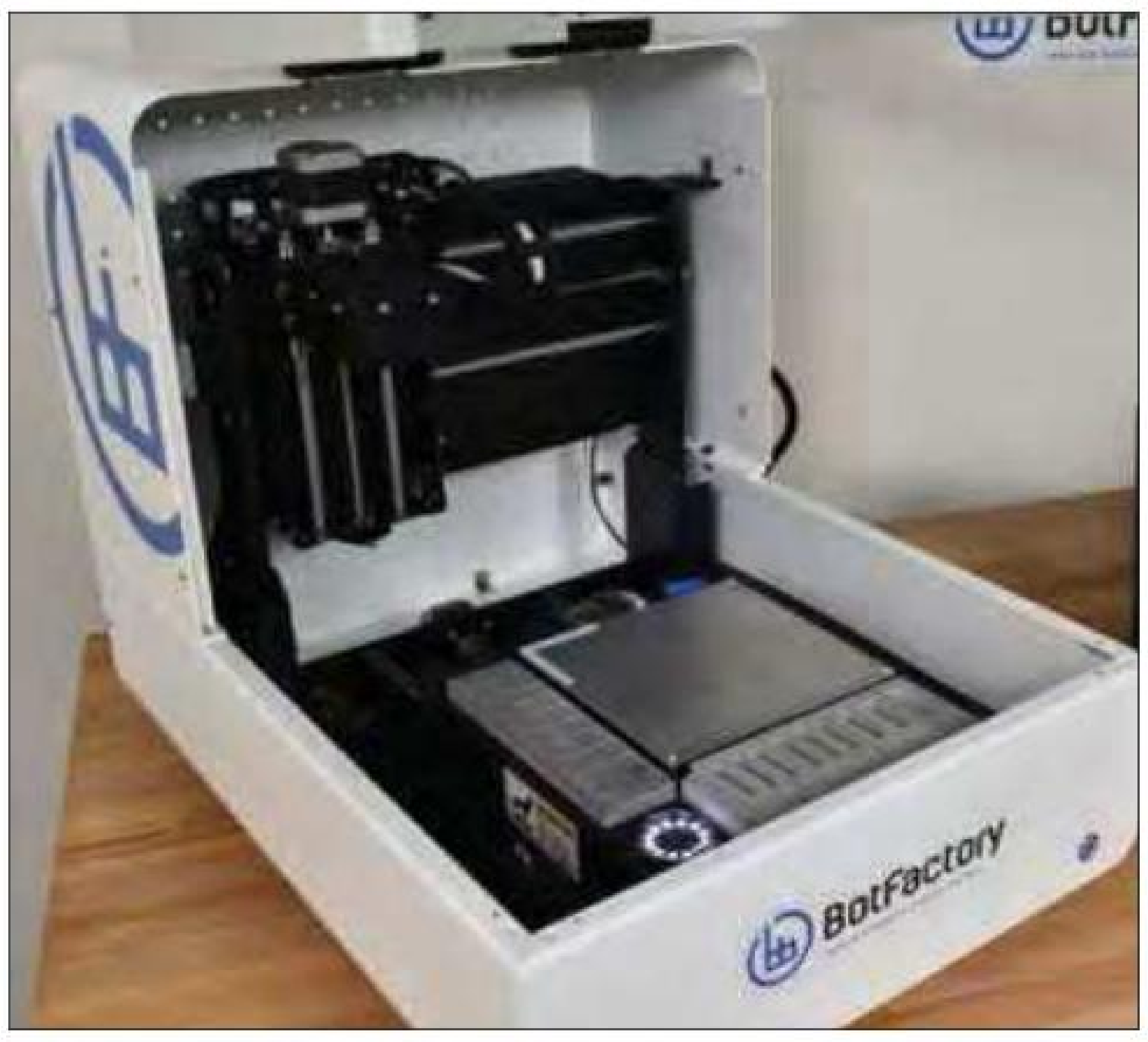


Fig.1. Meet the SV2. (Image: BotFactory)

On the other hand, in the same way that you can use a 3D printer to create interesting doodads and thingamabobs at home, there's a lot to be said for being able to fabricate your own PCB prototypes in the comfort of your workshop (also known as the dining room in my case, as my wife – Gina the Gorgeous – rarely fails to remind me). Well, by some strange quirk of fate, I was recently chatting with the founders of the BotFactory (**https://bit.ly/35yQsYH**). Their latest offering, the SV2 (Fig.1), which can sit comfortably on your workbench (if not so much with your bank statement), combines a conductive ink printer, solder paste extruder, pick-and-place machine, and reflow bed into a single product that allows you to prototype your PCBs in a matter of minutes.

At the other end of the scale, I recently ran across an interesting little item called *Print-a-Sketch* on the Hackaday website (**https://bit.ly/3vHdQOc**). This little scamp is a handheld device that lets you print electronic circuits on almost any surface using conductive ink. By means of an optical motion sensor (like the ones employed by gaming mice), the *Print-a-Sketch* knows where it is and how fast it's going. This allows its control circuitry to compensate for unsteady movement and straighten out freehand wobbly lines, for example, thereby providing a printing precision of less than 0.5mm.

It's life Jim, but not as we know it

As you are doubtless aware by now, my chum Steve Manley plays a huge role in many of the hobby projects I write about in my *Cool Beans* columns in *Practical Electronics* (*PE*). Steve is based in the UK, while I hang my hat in the US, but the wonders of the internet allow us to collaborate as though we lived just around the corner from each other. To be honest, Steve oftentimes does the bulk of the work while I scamper around reaping the benefits (we all have our roles to play). As a case in point, consider the animatronic robot head we've been developing.

The way this all came about had its roots in the tail end of 2021 when I created a couple of pseudo robot heads, each of which used two of our *SMADs* (*Steve and Max's Awesome Display*) as eyes (see *PE*, September, October, and November 2021). A little later (*PE*, December 2021), our illustrious *PE* publisher, Matt Pulzer, proposed that I add some sort of motion to my robot heads. I'm no longer sure who said what, when, or why, but – as part of this – I ended up perusing and pondering an interesting **Hackaday.com** column written by Danie Conradie (**https://bit.ly/3KjHzRv**). In turn, Danie's column introduced me to an ingenious automated artifact created by James Bruton (Fig.2).

This little rascal (the artifact, not James) is intended to provide a platform to implement lifelike animation. The problem James set out to address is rooted in the fact that hobby servos (which we will be

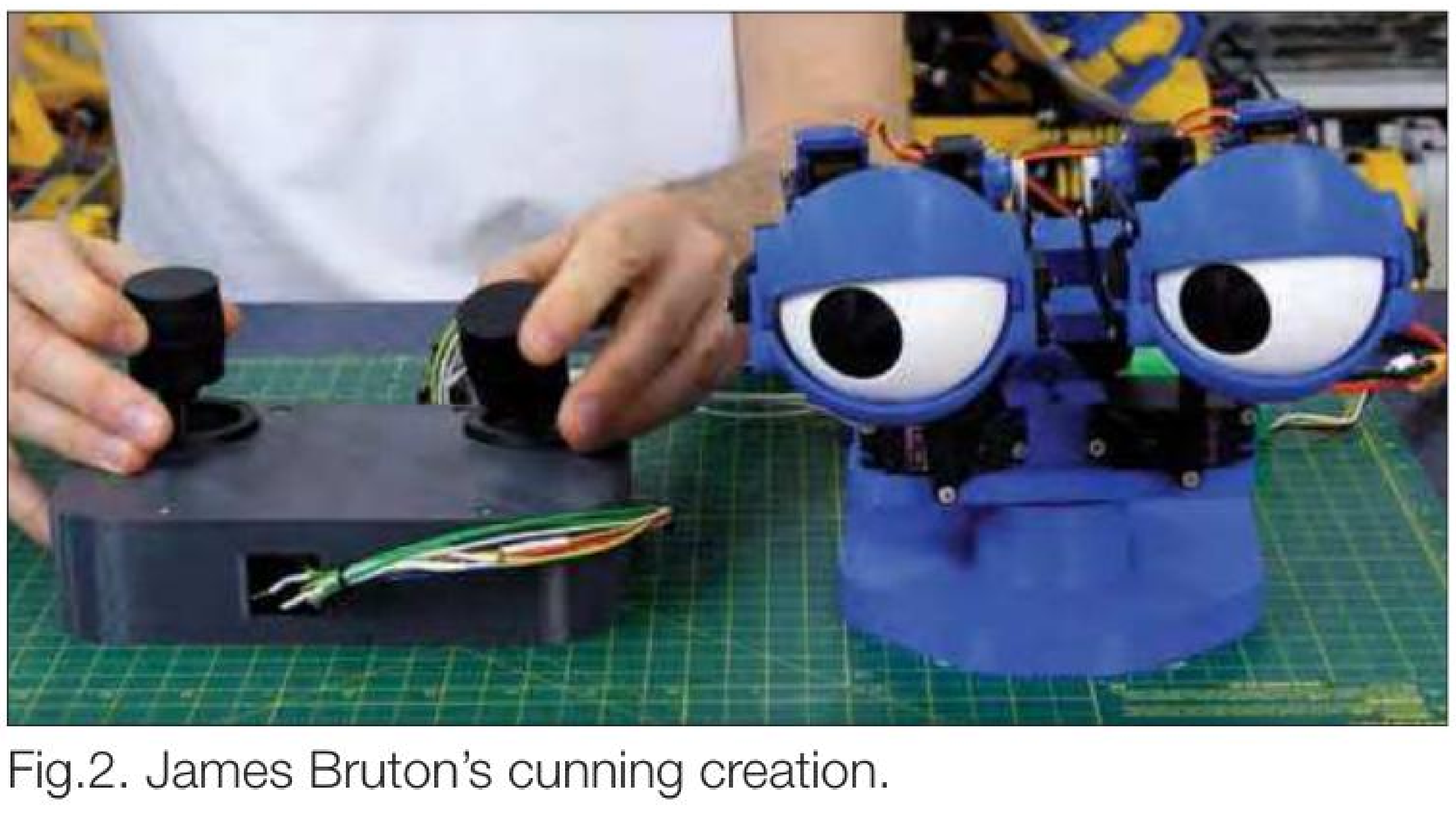


Fig.2. James Bruton's cunning creation.

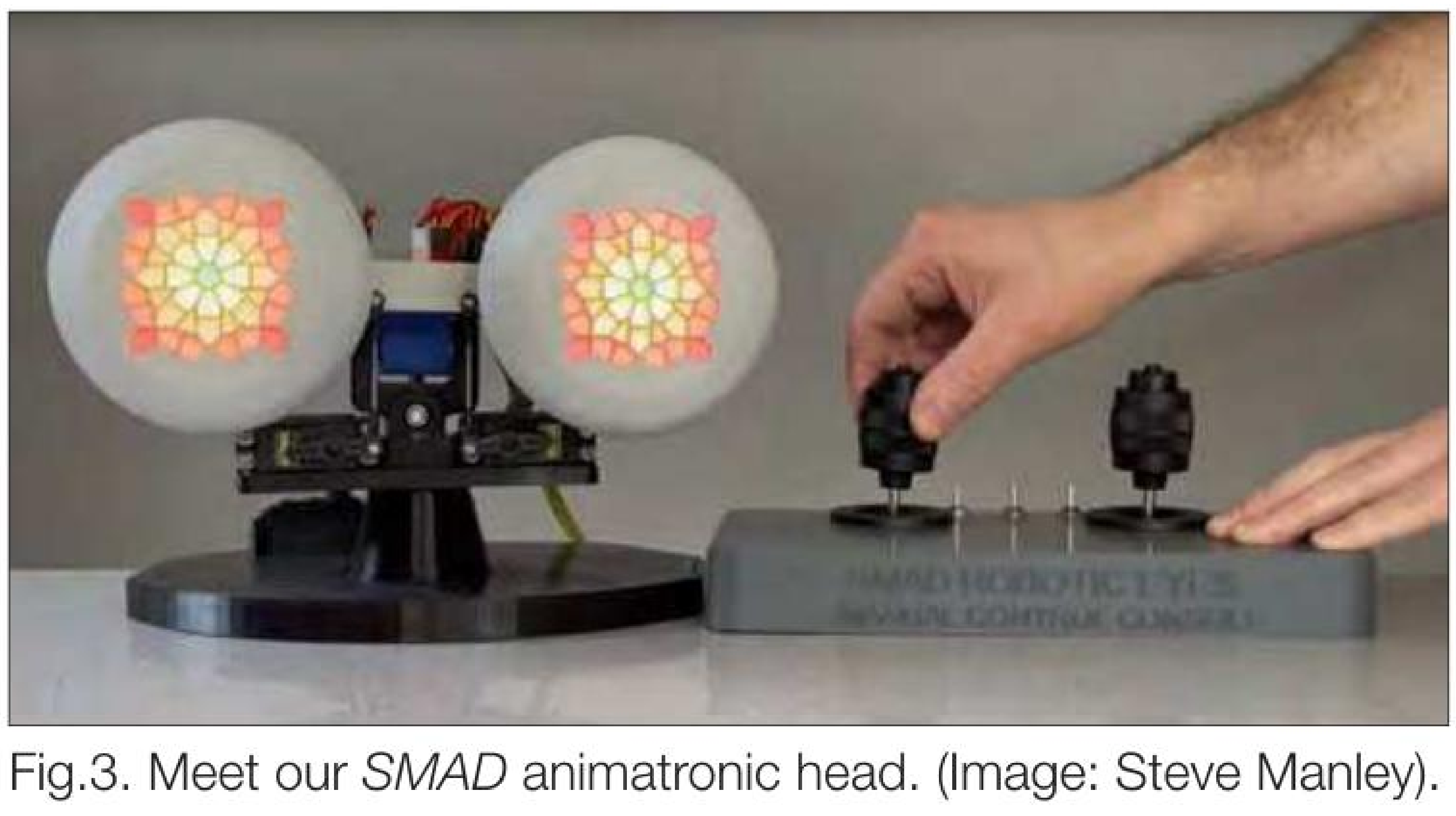


Fig.3. Meet our *SMAD* animatronic head. (Image: Steve Manley).

discussing in next month's *Cool Beans* column) move at a constant speed towards their specified target. This isn't an issue for many purposes, but it can detract from the sense of realism in animatronic applications. When you come to think about it, very little bodily motion occurs at constant speed. Instead, when we move parts of our body like our head and eyes, those parts are typically either accelerating or decelerating. If a loud sound occurs to one side of me, for example, the muscles in my neck will quickly accelerate my head in the target direction and then slow it down gradually as it reaches its desired destination. I have no doubt that the techniques James describes will make their way into our own animatronic offering in the fullness of time, speaking of which...

Holding my head in my hands

When we commenced work on our animatronic head, I started to experiment with some simple off-the-shelf pan-and-tilt mechanisms. Meanwhile, Steve fired up his Fusion 360 integrated CAD, CAM, CAE, and PCB software (**https://autode.sk/3hVxGNv**). It wasn't long before Steve was using his trusty 3D printer to create a thing of beauty and a joy to behold.

In an earlier column (*PE*, March 2022) I showed photos of my rudimentary prototype platform and contrasted it to Steve's captivating control console. I also presented an image illustrating Steve's awesome approach to using two servos to provide pan-and-tilt functionality for one of the eyes. You can see an animation of this movement on my *Cool Beans Blog* channel on YouTube (**https://bit.ly/3GcVTJK**).

As a slight aside, following that column and having watched the video, *PE* community member Ken Wood, who is even more passionate in his use of parentheses than your humble narrator, emailed me to say: 'Hi Max, regarding your mate's pan-and-tilt mechanism, as another approach, articulated "attachments" on the far end of an arm can be operated remotely by push-pull through two Bowden cables (the type of thing used for bicycle brake cables, and even manual gearbox shifters in cars instead of the complicated linkages used these days). The mechanism in your article could place the eye swivel away from the servos and have the servo arms linked through Bowden cables (if the servos are strong enough). Bowden cables provide a DIY alternative to hydraulics (admittedly without the force magnification) and (with careful design) can be made to flex around intermediate articulated joints (which might also be operated by more cables). The key is to keep all the cables in the same plane, parallel with the rotational axis, so that there is no differential change of length as the joint flexes. Even more interesting articulations can be achieved by similar mechanisms. Take a corrugated tube (ie, one that flexes) and run four (non-sheathed) cables down it (spaced around the perimeter). Pulling on any one cable will cause the tube to bend in that direction (like an elephant's trunk). Spiral the cables in opposite directions and the tube can be made to twist. In this example, the cables are acting like tendons and the springiness of the tube provides the restoring force (like opposing muscles).' Well, this is certainly food for thought, but we digress...

Since that earlier column, Steve has finished work on his animatronic noggin (Fig.3). For your delectation and delight, Steve has uploaded a video to YouTube that presents this bodacious beauty in all its glory (**https://bit.ly/3sMi6Kk**).

If you are interested in creating one of these awesome artifacts for yourself, I will be discussing more details regarding the servo motors and breakout boards (BOBs) we used in my next column. Also, Steve has very kindly made his 3D design files available. You can download a compressed ZIP (file **CB-May22-01.zip**) containing these design files from the May 2022 page of the *PE* website (**https://bit.ly/3oouhbl**).

Next, we'll work on the software, including our realisation of the lifelike animation techniques presented by James Bruton discussed earlier. The fabulous news, however, is that Steve very kindly created a second *SMAD* animatronic head and control console for yours truly. Just a few days ago, as I pen these words, this little rapscallion arrived at my home, thereby placing me in a position to proudly proclaim that I'm sitting here holding my head in my hands (which isn't something you expect to find yourself saying on a daily basis).

Don't speak geek!

I'm sure you remember me mentioning my chum Paul Parry on occasion. Paul is the owner of Bad Dog Designs from whence he creates marvelous masterpieces of a Nixie tube nature (**https://bit.ly/3sMFWps**). Several years ago, Paul introduced me to Dr Lucy Rogers, who is an author, inventor, and a visiting professor of engineering, creativity, and communication at Brunel University London.

As I said in a recent blog: 'Even if you are the geekiest of geeks or the nerdiest of nerds, speaking in the patois of the geek is not recommended. I can't tell you how often I've seen peoples' eyes glaze over when I'm talking to them… and things are even worse when I'm speaking geek.' The point of all this is I just heard Dr Lucy is offering a suite of 'Online Communication Courses by a Person in Tech for People in Tech' (**https://bit.ly/35xEG0w**).

The way things were

These days we are spoiled by the power and performance offered by digital computers. I still find it hard to believe that it's possible to purchase a microcontroller development board like a Seeedunio XIAO that's only 0.93-inch x 0.69-inch (23.5 x 17.5 mm) in size boasting a 32-bit Arm Cortex-M0+ processor running at 48MHz with 256KB of Flash memory and 32KB of SRAM for what essentially amounts to pocket change (**https://bit.ly/3IPpSc2**).

This is a far cry from the way things were in 1975 when I took my first tentative steps on the path to my BSc in Control Engineering at Sheffield Hallam University. At that time, the only digital computer available to us was a monstrous mainframe that lived in its own building. I remember writing my first program for this beast in a computer language called *Fortran* (FORMula TRANslator). The initial step was to capture the code using pencil and paper. Next, I keyed this program into a Teletype machine, which converted each line of text into holes in a punched card. I then hand-carried my 'deck of cards' to the computer building and handed it over to some surly individual lurking furtively behind the reception desk. When I returned a week later, I was presented with my original deck accompanied by a scrap of paper bearing a hand-scrawled note saying, 'Missing comma on line 2.' Arrggghh (and I mean that most sincerely); couldn't they have added that comma for me? The end result of this modus operandi was that it could easily take most of a semester to get even the simplest of programs to produce reasonable results.

The only computer that physically resided in the engineering department was an analogue beauty, similar in nature to the one shown in Fig.4. The idea here

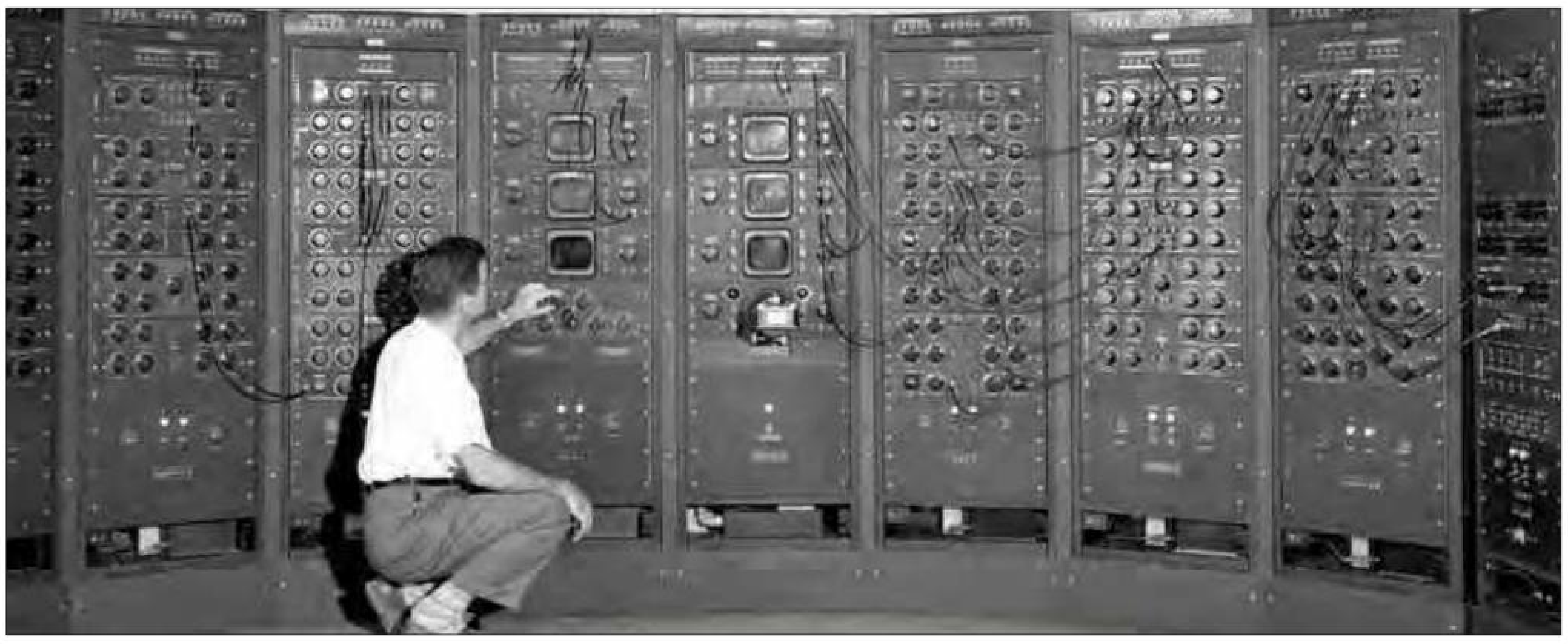


Fig.4. Analogue computer, Lewis Flight Propulsion Laboratory circa 1949. (Image: NASA)

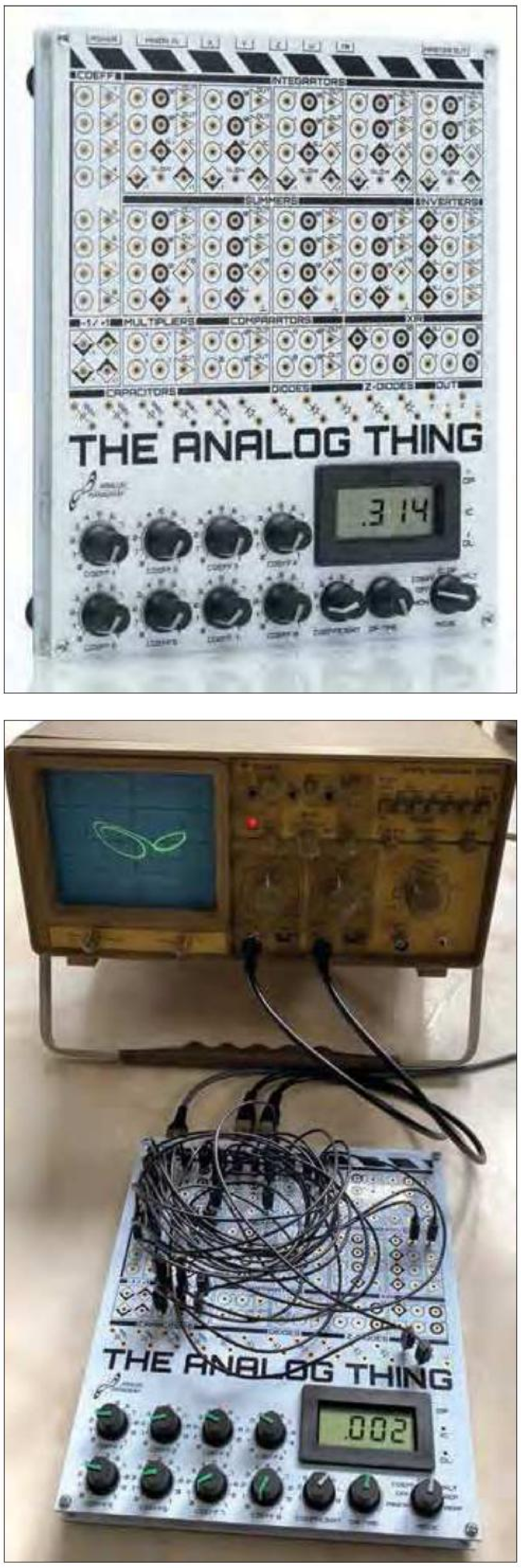


Fig.5. *The Analog Thing* (*THAT*). (Image: Anabrid)

is that you have lots of small analogue modules, each performing some function like comparing two analogue signals to see which is bigger (has the higher voltage), adding two analogue signals together, multiplying two analogue signals, or integrating an analogue signal over time. There were also a bunch of potentiometers (variable resistors) that were used to establish coefficient values. The inputs and outputs of the various modules were connected using cables with jack plugs on each end (unless you've done this yourself, you have no idea how deucedly difficult it was to debug a setup that wasn't working as planned).

One of the downsides to this form of analogue computing is lack of repeatability because – although they might be in the same ballpark – the results from multiple runs always have slight differences. Also, small initial errors can be compounded and amplified from stage to stage. Having said this, what may surprise people who haven't used this type of machine is that analogue computing and analogue signal processing (ASP) can be extremely efficacious when it comes to modelling things like dynamic systems. As I recall, my first task was to model how the insides of a refrigerator would cool down when it was first powered up; also, how the internal temperature would change when the refrigerator's door was opened.

The Analog Thing (THAT)

The reason I'm waffling about this here is that, as seen in Fig.5, I was just made aware of a forthcoming analogue computer called *The Analog Thing* (*THAT*) (**https://bit.ly/370WEZH**). I fear I must be getting old, because I initially thought the 'THAT' was part of this unit's name. It took me several seconds to realise that the 'THAT' was in fact an abbreviation of 'The Analog Thing' (colour me confused).

In addition to eight coefficient potentiometers, we have five integrators, four summers, two comparators, two multipliers, and a panel meter. There are also X, Y, Z, and U output ports that can be used to drive things like an oscilloscope, plus there are Master and Minion ports that allow multiple *THAT's* to be daisy-chained together to implement arbitrarily large programs. I must admit that I'm sorely tempted to 'splash the cash' for one of these little beauties. I find I have a strange desire to create a convoluted function and then spend an inordinate amount of time debugging the rat's nest of cables. If nothing else, doing so would take me on a trip down memory lane to the days of my youth.

But wait, there's more, because one of the things that attracted me to the *THAT* in the first place is that I've been contemplating a conundrum of an analogue nature with respect to the potentiometers (pots) Steve and I are using to control our animatronic heads. We will ponder this poser in a moment, but first...

Wandering into the weeds

You may have noticed that, to the untrained eye, I sometimes appear to wander off into the weeds, taking a deep dive into a seemingly random topic that tickles my fancy, but don't be fooled because there is method behind my madness (honest). In addition to being educational, fun, and interesting in their own right, the projects described in *PE* are intended to provide the foundations for our readers to develop their own circuits and systems in the future. Similarly, when we present tips, tricks, and techniques to address one situation, they are often applicable to other applications.

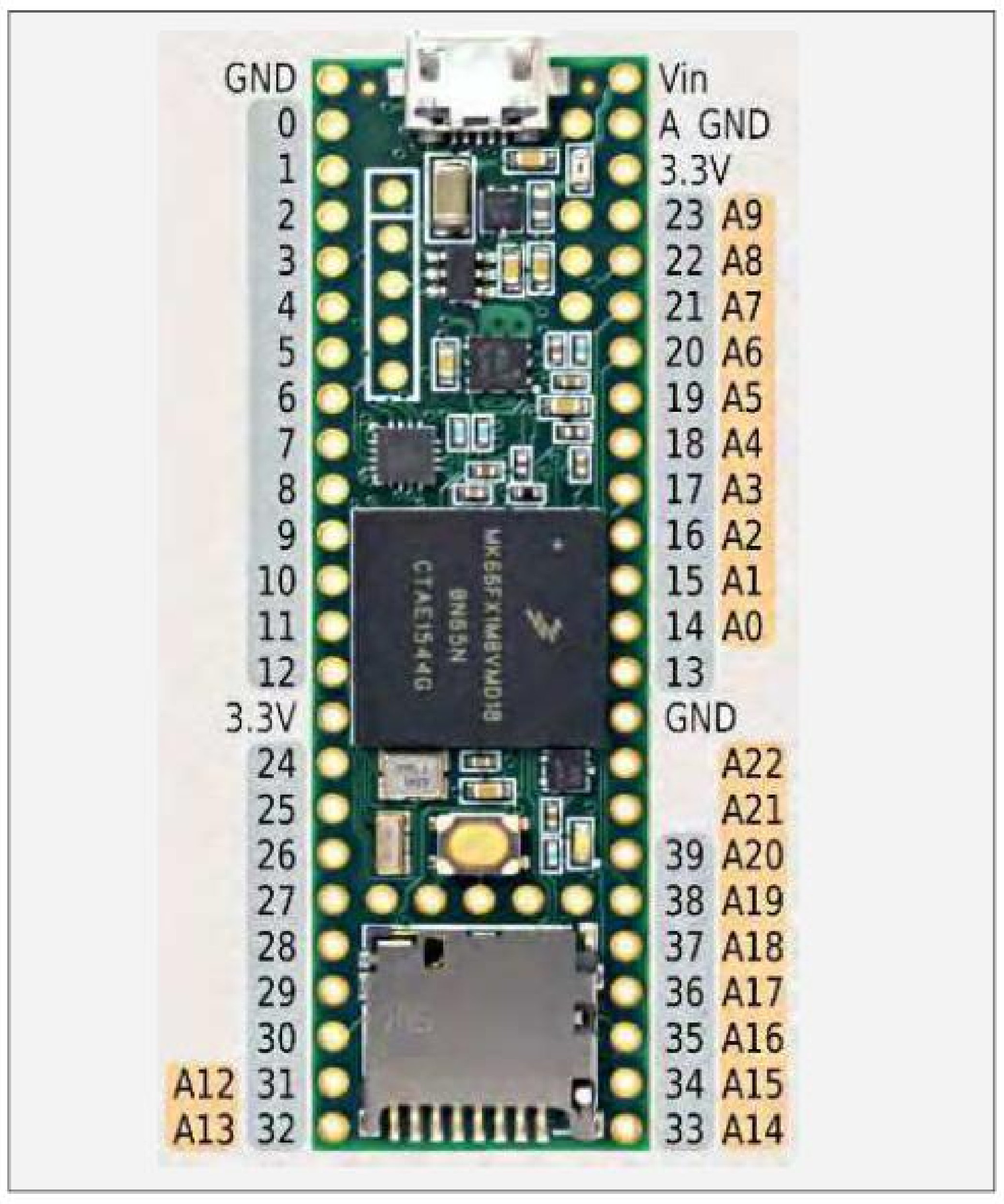


Fig.6. Top-side pins for the Teensy 3.6.

As just one example, in an earlier column (*PE*, October 2021), I described a technique using 2-dimensional (2D) arrays of 8-bit integers to define groups of LEDs used to form patterns on our *SMADs*. Two months later (*PE*, December 2021), I made mention of the fact that a member of the *PE* community, who we will call Simon (because that's his name), emailed me to say that reading my original column, and seeing this technique, had proved useful to him in creating an Arduino-based Morse code trainer.

I only mention this because we are about to take a short sideways tour into a topic that may not appear to be tremendously important at this moment in time. However, the techniques we discuss here will almost certainly prove to be of use in the days that are to come.

Your other left!

A couple of months ago (*PE*, January 2022), I introduced the JH-D400X-R4 10K 4-axis joysticks we are using to control our heads. At some stage in the future, we plan on using sensors and artificial intelligence (AI) to allow the heads to control themselves (be afraid, be very afraid), but that will be a tale for another day.

In reality, the JH-D400X-R4s are 3-axis devices with a pushbutton on top (their creators imaginatively cast this pushbutton as a fourth axis of control). Each joystick contains three 10kΩ pots, where each pot is centered around its halfway (5kΩ) position. If you move the pot around any of its axes and let go, it will return to its center position. Pushing the joystick forward or pulling it backward will affect one of the pots. Moving it to the left or the right will affect another of the pots. And rotating it clock-wise or anticlockwise will affect the remaining pot.

The way we've currently got things set up, by default, the left-hand joystick controls the head. Assuming you

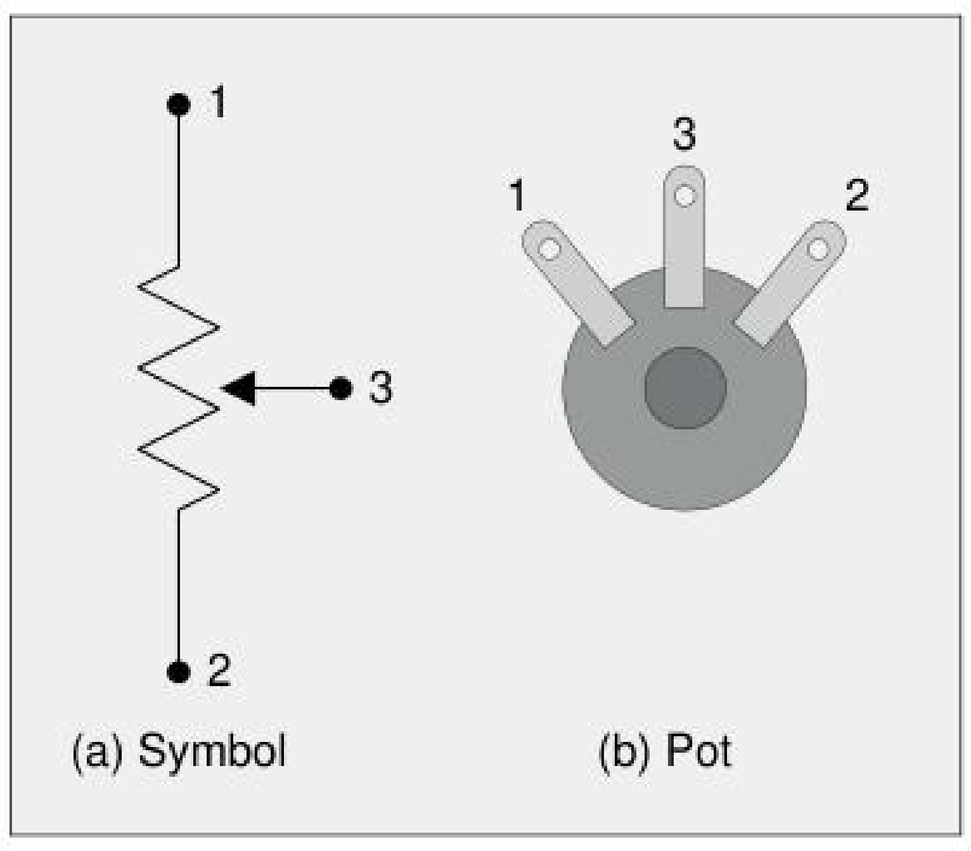


Fig.7. Pot symbol and graphical representation.

are facing the head, moving this stick to the left will cause the head to turn to your left (its right), while moving the stick to the right will cause the head to turn to your right (its left). Meanwhile, pushing the stick away from you will cause the head to tilt up, while pulling the stick towards you will cause the head to tilt down. This way of working makes sense to us, but it may not be intuitive to other users. Also, we must consider the case where the operator is standing behind the head. This is why we included three toggle switches on top of the control console – one reverses the actions of the left-right pan while another reverses the actions of the up-down tilt: the third? I'll never tell!

Still in the default mode, the right-hand joystick uses a similar methodology to control both *SMAD* eyes simultaneously, making them look left, right, up, and down. However, if you press the pushbutton on top of the left-hand joystick, the head will remain in its current position and the system will enter a new mode whereby the left and right joysticks control the left and right *SMAD* eyes, respectively. Pressing this button again will return the system to its default mode.

Why, Oh why?

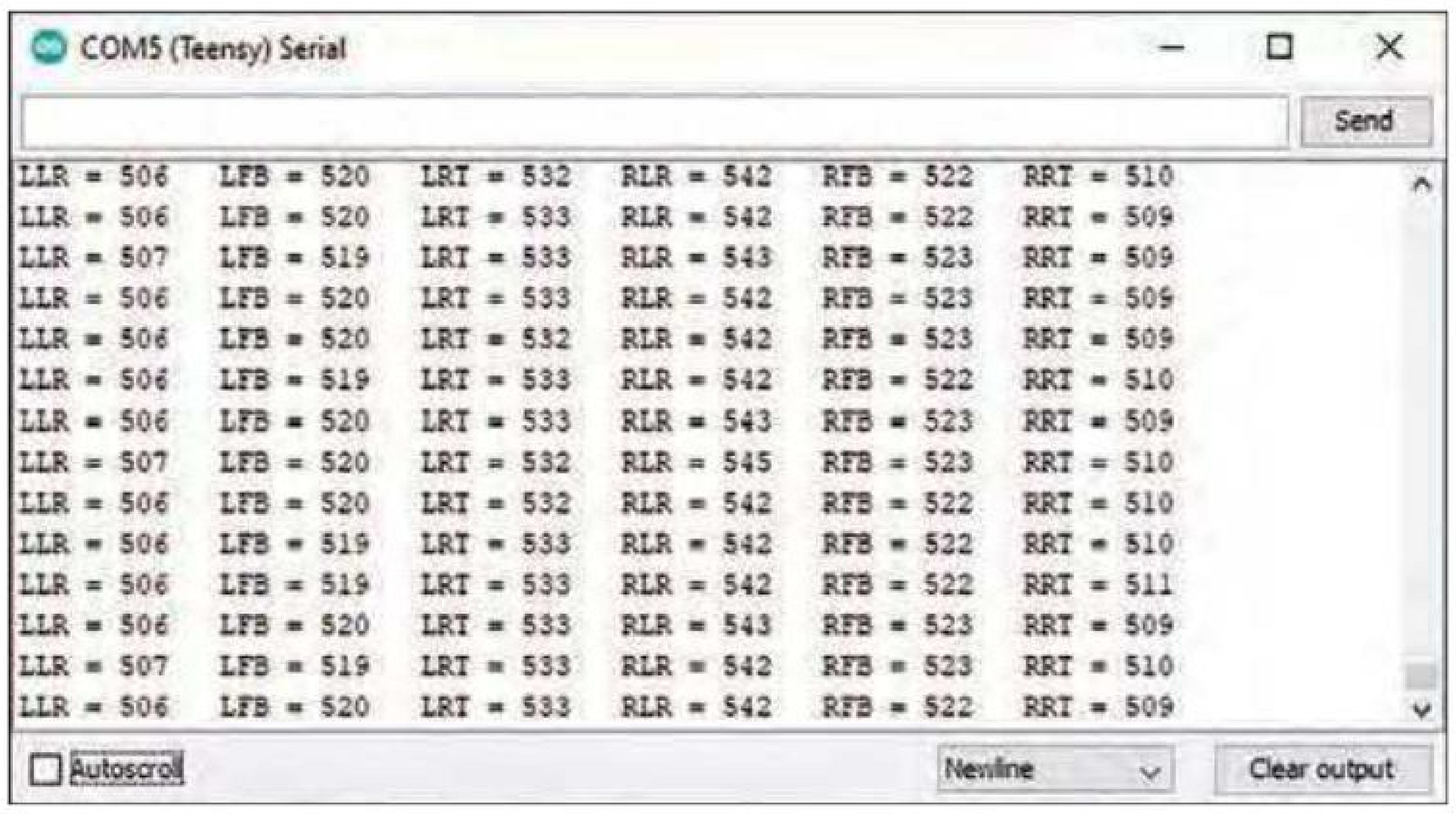
When I originally commenced experimenting with the early version of my animatronic noggin, I decided to use a Teensy microcontroller (**https://bit.ly/3J7pfeh**). I opted for a Teensy 3.6 because (a) I like its features in the form of a 32-bit Arm Cortex-M4F processor running at 180MHz with 256KB of RAM, 1MB of Flash, 58 digital general-purpose inputs/outputs (GPIOs), and 25 analogue inputs and (b) I happened to have one lying around.

The creators of the Teensy provide awesome pinout diagrams (**https://bit.ly/3J9lq8a**). A cutdown version of the top-side pinouts for the Teensy 3.6 is shown in Fig.6 (digital GPIOs 40 to 57 along with analogue inputs A10, A11, A23, and A24 are accessible via pads on the underside of the board).

I started by wiring the signal lines from the six pots on the joysticks to analogue pins A12 and A13 on the nearside of the Teensy and A14, A15, A16 and A17 on the far side. I then created a little sketch (program) that cycled around reading the values from the pots and displaying them on the Serial Monitor provided with the Arduino integrated development environment (IDE). I still remember the thrill of anticipation when I grasped the left-hand joystick and moved it left-right and forward-back, and I still remember the feelings of doom, despondency, and disappointment when... absolutely nothing happened.

Fortunately, rather than going off half-cocked into a debugging rampage, I first tried moving the right-hand joystick left-right and forward-back. Oh joy! The numbers on the screen changed accordingly. Next, I tried rotating both joysticks clockwise-anticlockwise and – once again – the values being displayed in the Serial Monitor updated as expected.

My trusty multimeter showed that all of the axes on both joysticks were reacting as they should and that the expected signals were reaching the Teensy's inputs. It also didn't take long to determine that the two wayward axes were connected to analogue inputs A12 and A13. Why weren't these inputs behaving themselves? I pondered possible points of failure, but nothing leapt out at me. Eventually, rather than beat my head against the wall, I simply unsoldered the signal wires feeding A12 and A13, connected them to A18 and A19, and everything worked as it should. Why, oh why should this be? I have no idea. Obviously, I wouldn't mind finding out (if you have any ideas, I'd love to hear them), but I'm not losing any sleep over this because life is too short.



```
LLR = 506   LFB = 520   LRT = 532   RLR = 542   RFB = 522   RRT = 510
LLR = 506   LFB = 520   LRT = 533   RLR = 542   RFB = 522   RRT = 509
LLR = 507   LFB = 519   LRT = 533   RLR = 543   RFB = 523   RRT = 509
LLR = 506   LFB = 520   LRT = 533   RLR = 542   RFB = 523   RRT = 509
LLR = 506   LFB = 520   LRT = 532   RLR = 542   RFB = 523   RRT = 509
LLR = 506   LFB = 519   LRT = 533   RLR = 542   RFB = 522   RRT = 510
LLR = 506   LFB = 520   LRT = 533   RLR = 543   RFB = 523   RRT = 509
LLR = 507   LFB = 520   LRT = 532   RLR = 545   RFB = 523   RRT = 510
LLR = 506   LFB = 520   LRT = 532   RLR = 542   RFB = 522   RRT = 510
LLR = 506   LFB = 519   LRT = 533   RLR = 542   RFB = 522   RRT = 510
LLR = 506   LFB = 519   LRT = 533   RLR = 542   RFB = 522   RRT = 511
LLR = 506   LFB = 520   LRT = 533   RLR = 543   RFB = 523   RRT = 509
LLR = 507   LFB = 519   LRT = 533   RLR = 542   RFB = 523   RRT = 510
LLR = 506   LFB = 520   LRT = 533   RLR = 542   RFB = 522   RRT = 509
```

Fig.8. Reading pots 1x times.

Baby steps

Just to ensure we're all wiggling our *derrieres* in the same conga line, let's remind ourselves that a pot has three terminals (Fig.7). Two terminals are connected to either end of a resistive element (10kΩ in our case), while the third is connected to a movable wiper. We're using our pots as voltage dividers, so we connect power to terminal (1) and ground (0V) to terminal (2), or vice versa (it doesn't really matter which way round these go because we can easily manipulate the resulting readings in software).

If you are using a microcontroller like an Arduino Uno, which is powered by 5V and whose GPIOs support 0 to 5V, then you will use a 5V supply for your pots. By comparison, although my Teensy 3.6 is powered by 5V, its GPIOs will only tolerate 0 to 3.3V, so I'm using a 3.3V supply to power my pots (this supply is generated by the Teensy's on-board regulator).

The Teensy 3.6 boasts a 10-bit analogue-to-digital converter (ADC), which is shared between the analogue inputs. Ten bits can support 2^{10} = 1,024 different binary values, which we number from 0 to 1,023. What this means is that the 0V to 3.3V signals on my pots' wipers will be seen by the Teensy as integers in the range 0 to 1,023.

Now let's return to my program that loops around reading the values from the six pots and displaying these values in the Arduino's Serial monitor (Fig.8). With respect to the LLR, LFR, LRT, RLR, RFB, and RRT annotations, the first letter indicates the left (L) or right (R) pot, while the remaining letters reflect the axis in question: LR = left-right, FR = forward-reverse, and RT = rotate.

To be honest, when I was wiring things up, I didn't spend any time connecting specific pots to explicit analogue inputs on the microcontroller because, as usual, this sort of thing is easy to sort out in software. This explains why we start by defining a constant value `NUM_POTS` to be 6 and then declare an array of integers called `PinsPots[]`, which we use to organise these inputs into the desired order:

```
PinsPots[NUM_POTS] = {A18, A14, A19, A17, A15, A16};
```

We also declare an array of integers called `PotVals[]`, which we use to store the values read from the pots. All this program does is loop around calling two functions with a one-second delay at the end of each iteration. The first function, `ReadPots()`, reads the analogue inputs and stores the values in `PotVals[]`, then the second function, `DisplayPotValues()`, reads the values out of `PotVals[]` and displays them in the Serial Monitor. The heart of the `ReadPots()` function is a simple `for()` statement:

```
for (int iPot = 0; iPot < NUM_POTS; iPot++)
{
  PotVals[iPot] = analogRead(PinsPots[iPot]);
}
```

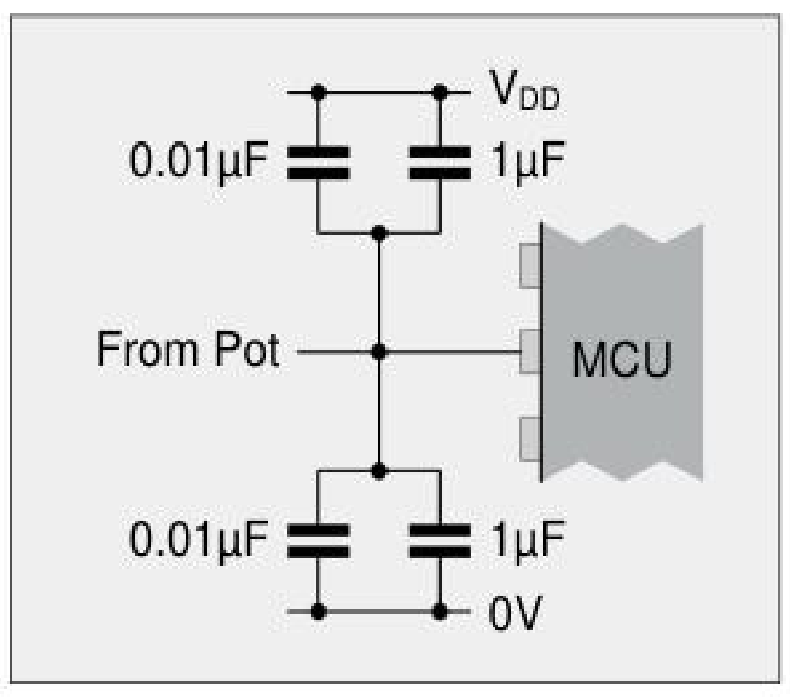


Fig.9. Using capacitors to mitigate noise.

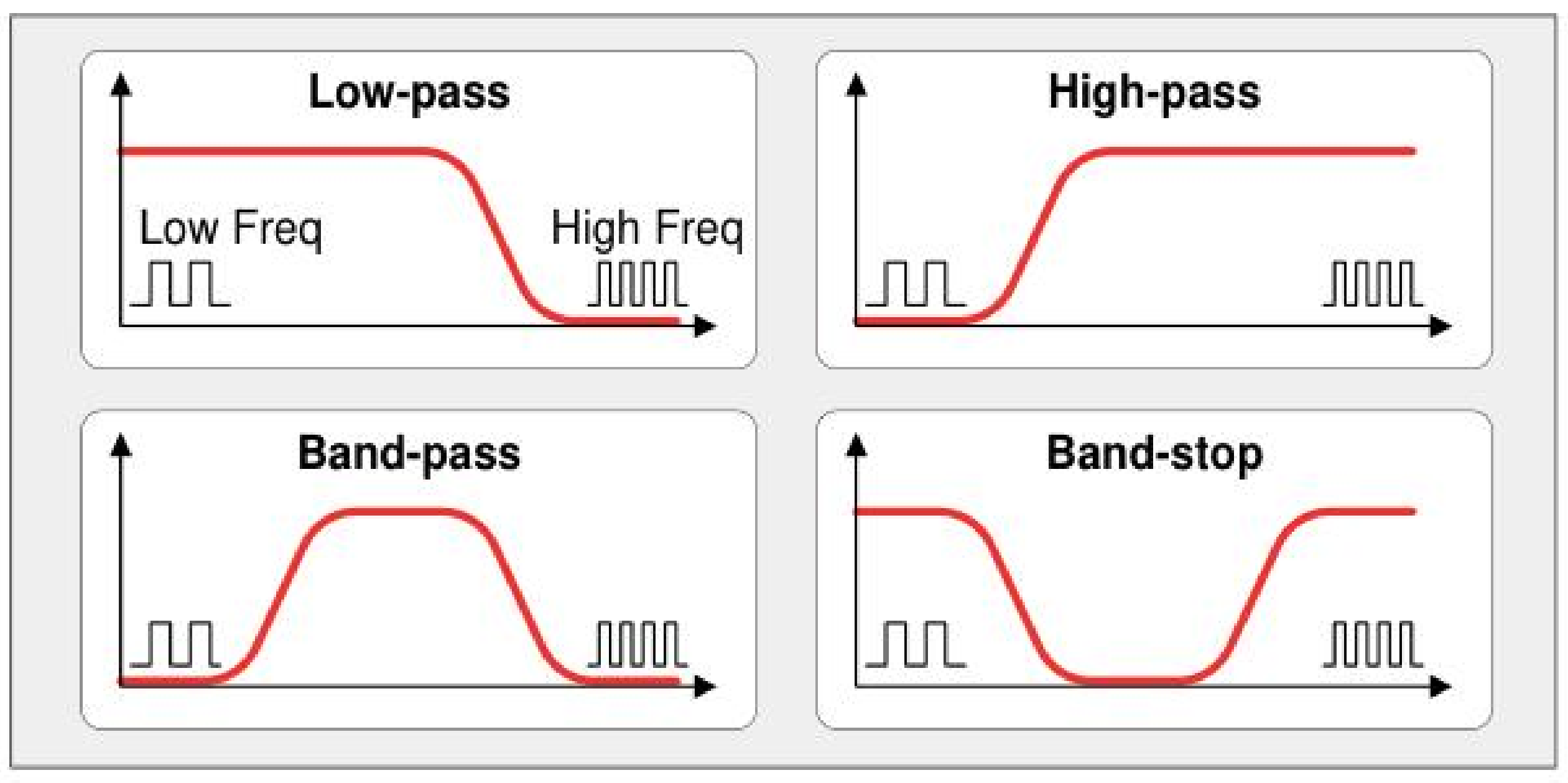


Fig.10. Four fundamental filters.

The only reason this is of interest is because of the ways in which we are going to evolve it. As usual, you can download this program from the *PE* website if you so desire (see file **CB-May22-02.txt**).

Wibbly wobbly

Remembering that the pots in our joysticks default to their center positions, we would expect all of the default readings to be 511. In reality, as you may have observed in Fig.8, each pot has its own center value (LLR = ~506, LFB = ~520, LRT = ~533, etc.), which is something we will have to account for at some stage in the future. Another aspect of this I hadn't considered is that when you move and subsequently release one of the joysticks, it may not return to the exact same center position. This is something else we will need to cogitate on in the days that are to come.

But the thing I want to focus on here is that, even when we aren't moving the joysticks, the values wobble around a little due to noise in the circuit and surrounding environment (eg, the RRT signal in Fig.8 varies between 509, 510, and 511). This noise could be coming from a variety of sources, such as the power supply or electromagnetic radiation from other devices in the vicinity.

On the one hand, for reasons that will become clear, the small amount of wobble we are seeing here isn't important in the case of our animatronic application. On the other hand, I'm a digital man by trade (you know where you are with 0 and 1 values), and I find wibbly wobbly signals to be a tad disconcerting, so I like to get rid of them given a chance.

I remember once joking to an analogue engineer friend that it was strange how the wobbles always appear on the least-significant bits (LSBs) and he quickly replied: 'That's what these bits are for!'

Where's the source?

Before we leap into action, one thing we might want to do is see if we can determine the source of the wobbles, especially if we were seeing a substantial amount of noise. One way to do this would be to move the joystick so that its output reads 0, which means its wiper is at the ground end of its travel. If we are still seeing the noise, then it's probably electromagnetic in origin. Next, we move the joystick so that its output reads 1,023, which means its wiper is at the power end of its travel. If we are still seeing the noise, then it may be originating in the power supply. In this latter case, another quick test would be to swap out the power supply for a battery; if the noise disappears, we've tracked down the culprit.

Are capacitors the answer?

With regard to the readings we are seeing from our pots, we can regard the wibble wobble on the LSBs as being (relatively) high-frequency noise. One solution to the sort of noise we're seeing here is to add some capacitors to our circuit. Apart from anything else, we want these capacitors to provide a low impedance path to the fast edges and high-frequency characteristics of electrostatic discharge (ESD) strikes, so any components we use should be physically small and mounted as close as possible to the microcontroller's input pins.

To be honest, you could write a book or two on this sort of thing (people have). For our purposes here, if we were to decide that capacitors were the way we wanted to go, then – for each analogue input – we would add a pair of capacitors (0.01µF and 1µF) in parallel (side-by-side) between the signal (analogue pin) and ground, and another pair between the signal and power (Fig.9).

In my case, I decided that I really didn't want to spend my Sunday afternoon soldering capacitors onto my prototype board (also, I hadn't thought to reserve any space for them), so I determined to opt for a software solution.

Fabulous filters

I'm afraid we need to make a slight digression. In physics, the term 'frequency' refers to the number of occurrences of a repeating event per unit of time. Frequency is expressed in units of hertz (Hz), where 1Hz is equivalent to one event per second. This means that a lower-frequency signal (like a man with a deep voice humming) has a smaller number of Hz, while a higher-frequency signal (like me squealing if I see a mouse) has a higher number of Hz.

If we wish to take a signal that is composed of a range of frequencies and remove some of these little rascals, then we can do so using some sort of filter. The four fundamental filter types are low-pass (which passes low frequencies and blocks higher frequencies), high-pass (which passes higher frequencies and blocks lower frequencies), band-pass, and band-stop (Fig.10). We can implement these filters in hardware or software.

Don't be average

One solution to our problem is to take multiple readings from each pot and then average them out (that is, sum 'n' samples and then divide the result by 'n'). For example, we might modify the heart of our `ReadPots()` function as follows (file **CB-May22-03.txt**):

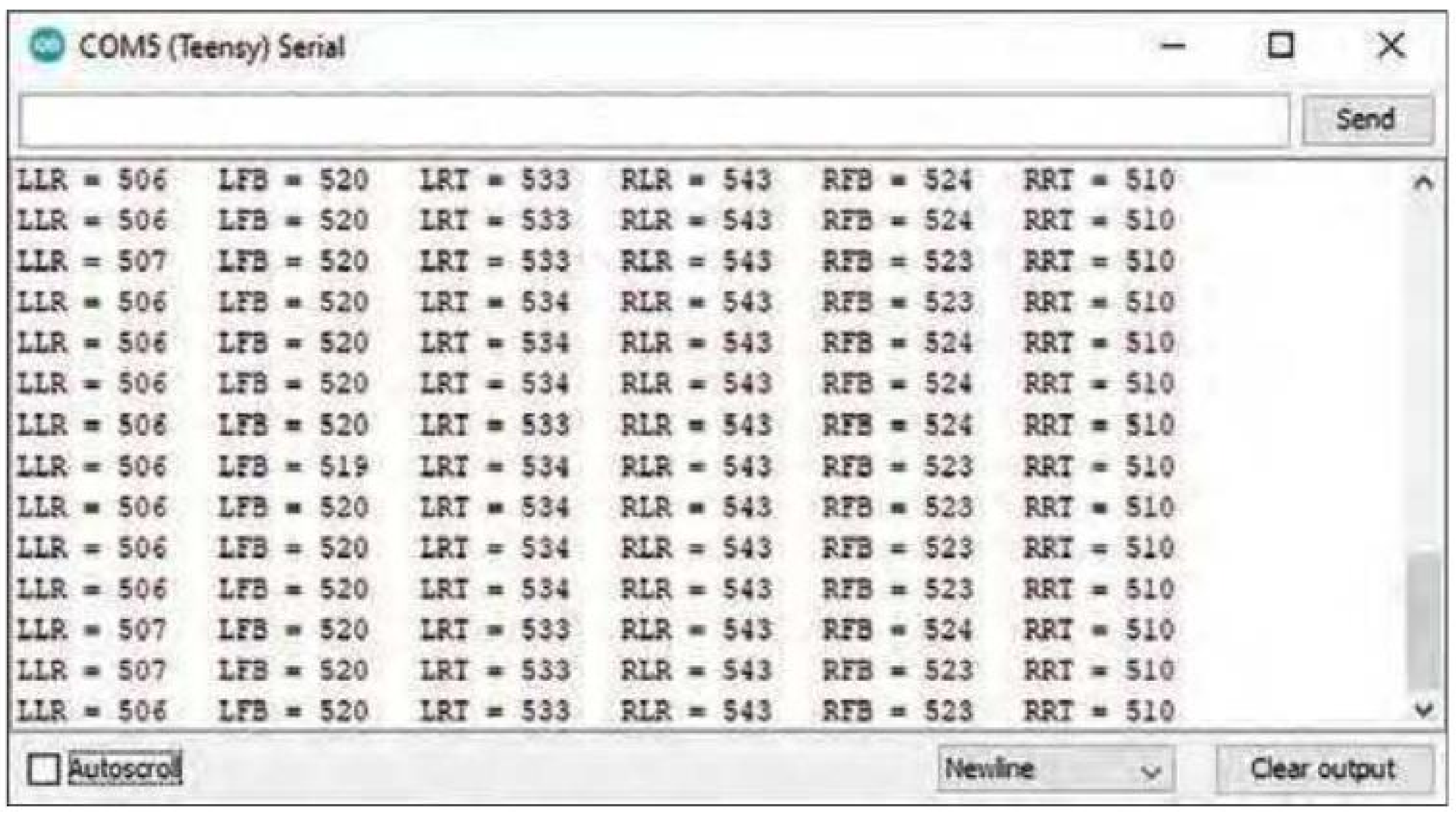
```
for (int iPot = 0; iPot < NUM_POTS; iPot++)
{
  PotVals[iPot] = 0;

  for (int iSmp = 0;
           iSmp < NUM_POT_SAMPLES; iSmp++)
  {
    PotVals[iPot] += analogRead(PinsPots[iPot]);
  }

  PotVals[iPot] /= NUM_POT_SAMPLES;
}
```

In this case, we perform all of the reads on the first pot, then on the second, then the third, and so forth. An alternative approach would be to start by taking a single reading from each pot, then return and take a second reading from each pot, and so forth (file **CB-May22-04.txt**). I'm not sure if there is any official determination as to which approach is the most efficacious, although I do have a 'gut feeling' that the second technique may have a slight edge.

On the off chance you were wondering, what we are doing here is implementing a very primitive form of finite impulse response (FIR) low-pass filter. The reason for the 'finite' qualifier is that we are using a finite number of samples. For the purposes of these discussions, I started by setting `NUM_POT_SAMPLES` to 5 (Fig.11).



```
LLR = 506   LFB = 520   LRT = 533   RLR = 543   RFB = 524   RRT = 510
LLR = 506   LFB = 520   LRT = 533   RLR = 543   RFB = 524   RRT = 510
LLR = 507   LFB = 520   LRT = 533   RLR = 543   RFB = 523   RRT = 510
LLR = 506   LFB = 520   LRT = 534   RLR = 543   RFB = 523   RRT = 510
LLR = 506   LFB = 520   LRT = 534   RLR = 543   RFB = 524   RRT = 510
LLR = 506   LFB = 520   LRT = 534   RLR = 543   RFB = 524   RRT = 510
LLR = 506   LFB = 520   LRT = 533   RLR = 543   RFB = 524   RRT = 510
LLR = 506   LFB = 519   LRT = 534   RLR = 543   RFB = 523   RRT = 510
LLR = 506   LFB = 520   LRT = 534   RLR = 543   RFB = 523   RRT = 510
LLR = 506   LFB = 520   LRT = 534   RLR = 543   RFB = 523   RRT = 510
LLR = 506   LFB = 520   LRT = 534   RLR = 543   RFB = 523   RRT = 510
LLR = 507   LFB = 520   LRT = 533   RLR = 543   RFB = 524   RRT = 510
LLR = 507   LFB = 520   LRT = 533   RLR = 543   RFB = 523   RRT = 510
LLR = 506   LFB = 520   LRT = 533   RLR = 543   RFB = 523   RRT = 510
```

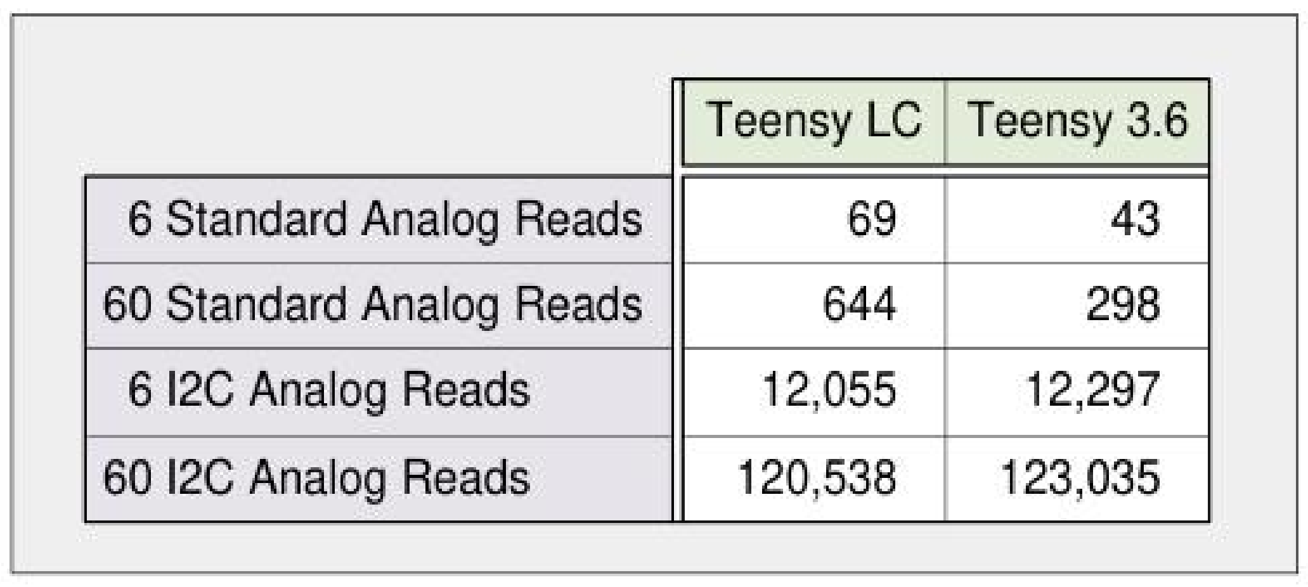
Fig.11. Reading the pots 5x times.

As we see, the results are significantly better than for our 1x samples, but there's still a little wibble wobble on some of the signals. We could keep on increasing our sample size – say using ten samples – but this causes us to run into a problem.

To control his animatronic head, Steve is using a Teensy LC, which boasts a 32-bit Arm Cortex-M0+ processor running at 48MHz with 8KB of RAM, and 62KB of Flash. One big point is that the Teensy LC has fewer GPIO pins at its disposal, so Steve decided to feed the signals from his pots into two 4-channel 12-bit ADC breakout boards from Adafruit (**https://bit.ly/3w8xYt3**). The Teensy LC communicates with these boards using a 2-wire I^{2}C interface, which means he devotes only two pins to reading the signals from all six pots. However, there is a price to pay with respect to the time overhead associated with using the I^{2}C.

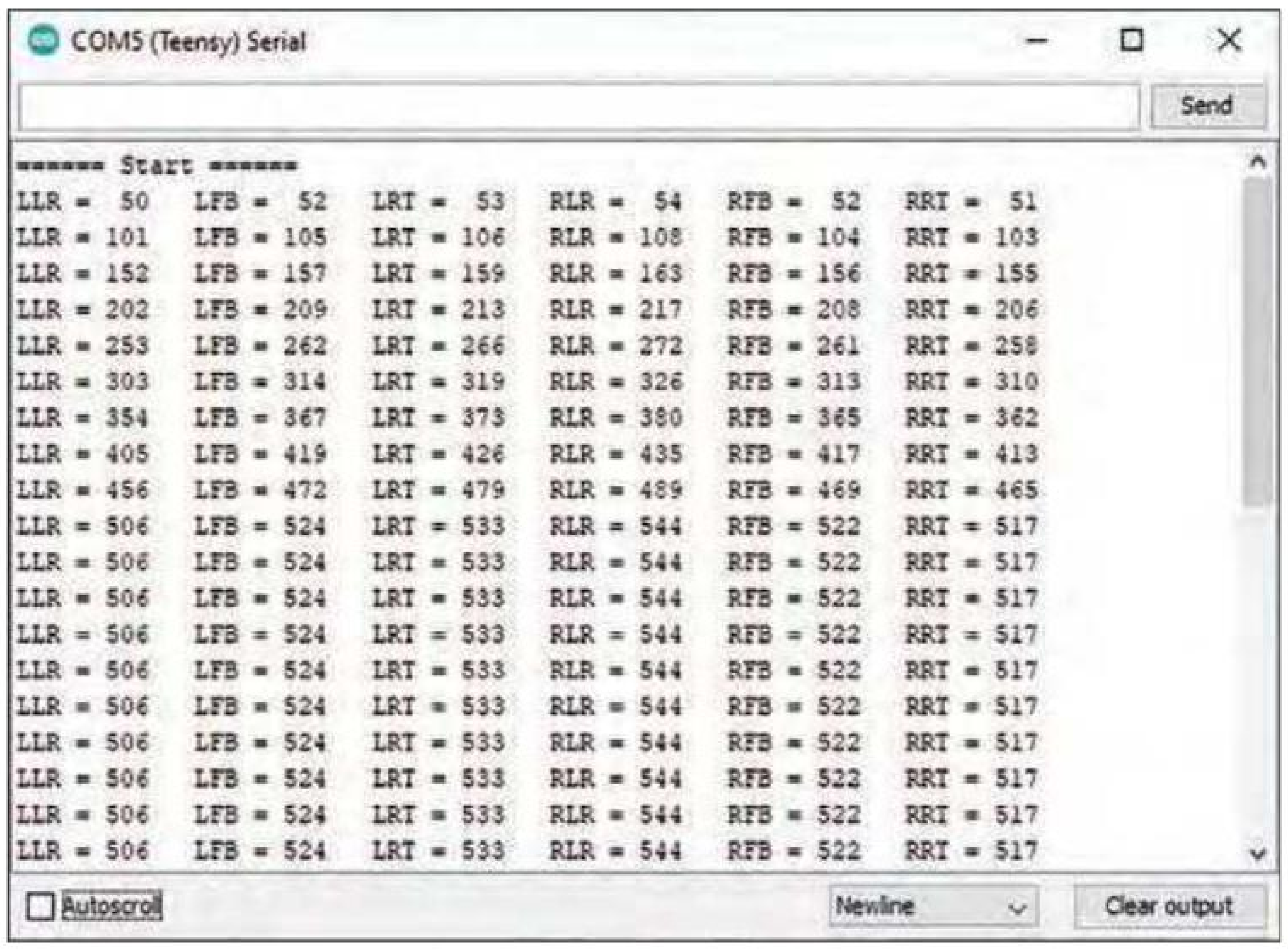
To understand just how much overhead we're talking about, Steve created a simple test program (file **CB-May22-05.txt**) to compare the times (in microseconds) it takes to read six pots one time and ten times; also, to perform these reads directly from an analogue input and then via an I^{2}C breakout board. Just for giggles and grins, I used Steve's program to test my Teensy 3.6. The results from both processors are shown in Fig.12.

Not surprisingly, considering their relative clock speeds, the Teensy 3.6 performs the direct reads faster than the Teensy LC, but the I^{2}C reads take about the same amount of time (actually, the Teensy 3.6 is a tad slower with respect to the I^{2}C reads, but I have no clue why this should be).



	Teensy LC	Teensy 3.6
6 Standard Analog Reads	69	43
60 Standard Analog Reads	644	298
6 I2C Analog Reads	12,055	12,297
60 I2C Analog Reads	120,538	123,035

Fig.12. Results of analogue reads (in µs).



```
====== Start ======
LLR =  50   LFB =  52   LRT =  53   RLR =  54   RFB =  52   RRT =  51
LLR = 101   LFB = 105   LRT = 106   RLR = 108   RFB = 104   RRT = 103
LLR = 152   LFB = 157   LRT = 159   RLR = 163   RFB = 156   RRT = 155
LLR = 202   LFB = 209   LRT = 213   RLR = 217   RFB = 208   RRT = 206
LLR = 253   LFB = 262   LRT = 266   RLR = 272   RFB = 261   RRT = 258
LLR = 303   LFB = 314   LRT = 319   RLR = 326   RFB = 313   RRT = 310
LLR = 354   LFB = 367   LRT = 373   RLR = 380   RFB = 365   RRT = 362
LLR = 405   LFB = 419   LRT = 426   RLR = 435   RFB = 417   RRT = 413
LLR = 456   LFB = 472   LRT = 479   RLR = 489   RFB = 469   RRT = 465
LLR = 506   LFB = 524   LRT = 533   RLR = 544   RFB = 522   RRT = 517
LLR = 506   LFB = 524   LRT = 533   RLR = 544   RFB = 522   RRT = 517
LLR = 506   LFB = 524   LRT = 533   RLR = 544   RFB = 522   RRT = 517
LLR = 506   LFB = 524   LRT = 533   RLR = 544   RFB = 522   RRT = 517
LLR = 506   LFB = 524   LRT = 533   RLR = 544   RFB = 522   RRT = 517
LLR = 506   LFB = 524   LRT = 533   RLR = 544   RFB = 522   RRT = 517
LLR = 506   LFB = 524   LRT = 533   RLR = 544   RFB = 522   RRT = 517
LLR = 506   LFB = 524   LRT = 533   RLR = 544   RFB = 522   RRT = 517
LLR = 506   LFB = 524   LRT = 533   RLR = 544   RFB = 522   RRT = 517
LLR = 506   LFB = 524   LRT = 533   RLR = 544   RFB = 522   RRT = 517
```

Fig.13. Reading the pots 10x times with a rolling average.

Rolling along

So, our conundrum is that we want to increase the number of samples, but we don't want to accept the hit in terms of time. Happily, there is a solution to our conundrum, which is to maintain a rolling average (also known as a running average or a moving average). A rolling average is commonly used with time series data to smooth out short-term fluctuations and highlight longer-term trends or cycles. Once again, this is a simple type of FIR filter.

In this case, we commence by setting all of our values to 0. Each time around our loop, we take only a single sample from each pot. The trick is that we store the past 'n' samples. Whenever we are ready to check the results, we sum these 'n' samples and divide the result by 'n' (file **CB-May22-06.txt**).

The results of a rolling average using a sample size of 10 are shown in Fig.13. Observe how – since we start by initialising all of the sample values to 0 – the results gradually increase over the course of the first 10 iterations around the loop, after which all of the values remain rocksteady.

It's all meaningless

As I mentioned earlier, the small amount of wobble we were seeing prior to our rolling average solution isn't realistically of any import with respect to our animatronic application, which essentially means that our wibbly wobbly discussions above are meaningless in this context (I also noted that the techniques discussed here may prove to be of interest for other applications in the future, so all is not lost).

Why do I say this? Well, let's assume we don't do any frequency filtering and we return to using our raw readings from Fig.8. We introduced the concept of pulse-width modulation (PWM) in an earlier column (*PE*, March 2020). Suppose we wished to use the 0 to 1,023 readings from our pots to generate PWM signals to control LEDs, for example, where these PWM signals have a range of 0 to 255. This means we need to map our 0 to 1,023 source values onto corresponding 0 to 255 target values. In this case, the easiest way to do this is to divide our source values by 4 (which is equivalent to shifting them right by two bits). This essentially truncates the two LSBs, which is a form of amplitude modulation that discards the wibbly wobbly portion of our signals.

When it comes to the hobby servos we are using to control our animatronic noggins, we don't want any wibble wobble on the signals we read from our pots to be translated into jittery twitches on the head and its eyes. So, let's think this through. Although they are capable of a greater range of movement, we are currently rotating our servos through a range of only approximately –45° to +45°. Even assuming an accuracy of 0.5°, which I think is being generous, this means that I will be mapping the 0 to 1,023 values from my pots into the equivalent of 0 to 179 values used to drive my servos, which means I won't even see my two wibbly wobbly LSBs. (Similarly, Steve will be mapping the 0 to 4,095 values from his 12-bit ADCs onto the same 0 to 179 values used to drive his servos, which means he can discard his four wibbly wobbly LSBs.)

As usual, we've only touched upon a huge topic, but at least it gives us something to noodle on until we meet again.

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

Wind turbine for your garden

by Julian Edgar

Relatively low in cost and well-made, this turbine is ideal for experimenting with wind power.

Wind turbines now produce a major proportion of the world's renewable energy. Great strides have been made in their design, especially in the sheer scale of the turbines now used. However, for people wanting a small wind turbine for home use, the story's not been so good. Small scale wind turbines have remained expensive, typically costing around £300. However, things are changing – as this story shows. The wind turbine pictured here cost only a little over £100, including delivery. In addition to its low cost, it's surprisingly well made and has a useful output.

Will it work for you?

Wind turbines are not for everyone, so it's important before buying one to think carefully about your situation.

First, you need a place that has lots of wind. And that means not only strong winds, but winds that blow hard all year around. It all sounds obvious but it's easy to overlook these vital points. For example, the turbine shown here, as with many similar turbines, has a claimed 'start-up' wind speed of 2m/s (metres per second) – that's just over 7km/h. However, I found that to get a useful output, the wind speed needs to be more like 20km/h. Depending on your location, 20km/h might be regarded as a windy day – or just a gentle breeze!

Where I live, we tend to get afternoon and evening gully winds. That is, they blow quite strongly, but only for a few hours a day. (Some coastal areas have a similar wind pattern, with sea and land breezes.) So I am likely to get a useful output from the wind generator for less than one-tenth of the day. Without getting too far ahead of myself, that makes the turbine ideal for charging a battery that runs a low-current alarm, or lights that can be manually operated – for example, in an outhouse or shed. But in my situation, there would not be enough harvested energy to run a powerful light that is switched on all night, for example.

Second, wind speeds increase dramatically with height above the ground. The wind speed at the top of an 8m-high tower can be twice that measured at 1.5m elevation. So, for best results, you will need to mount the turbine on a tower or pole. Again, for some people that will be a minor issue, but for others it might be a deal-breaker.

Finally, if you live in a sunny environment, it will likely be more cost-effective to use PV solar panels than a wind turbine. Even if you need a larger battery, so allowing for (say) a week without sunshine, you are still likely to be finically ahead of buying a wind turbine.

So, all doom and gloom? Not at all. If you live in a windy location that doesn't get a lot of sunshine, you have space to put up a tower and want to power something that has a low average current draw, this wind turbine will work well. So, let's take a look at it.

The wind turbine

The turbines (plural – because I liked the product so much, I ended up buying three) were purchased from Banggood. There is a wide variety of wind turbines available, all with different descriptions and claiming different power outputs. However, the one I bought can be recognised by these characteristics:

- Downturned tail with a distinctive patterned cut-out
- Forward part of the housing has heat-sink fins
- Five blades with a 1200mm diameter
- Cast flange to which the blades bolt
- Cast alloy mast clamp
- Electronic controller

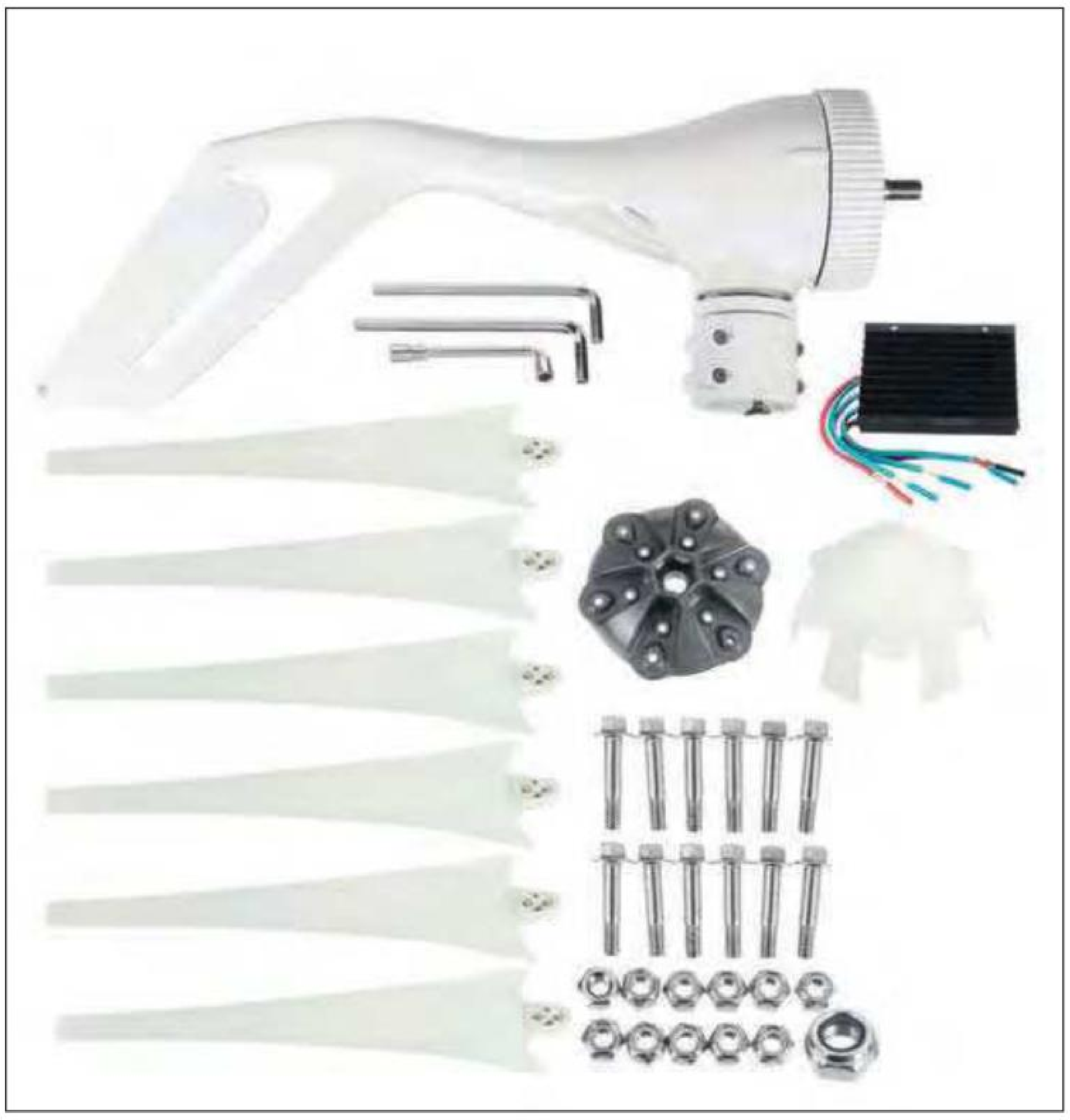


Fig.1. The disassembled wind turbine. The quality is very good, but the nylon blades and plated mild steel fasteners should be protected with a coat of paint. (Pic: Banggood)

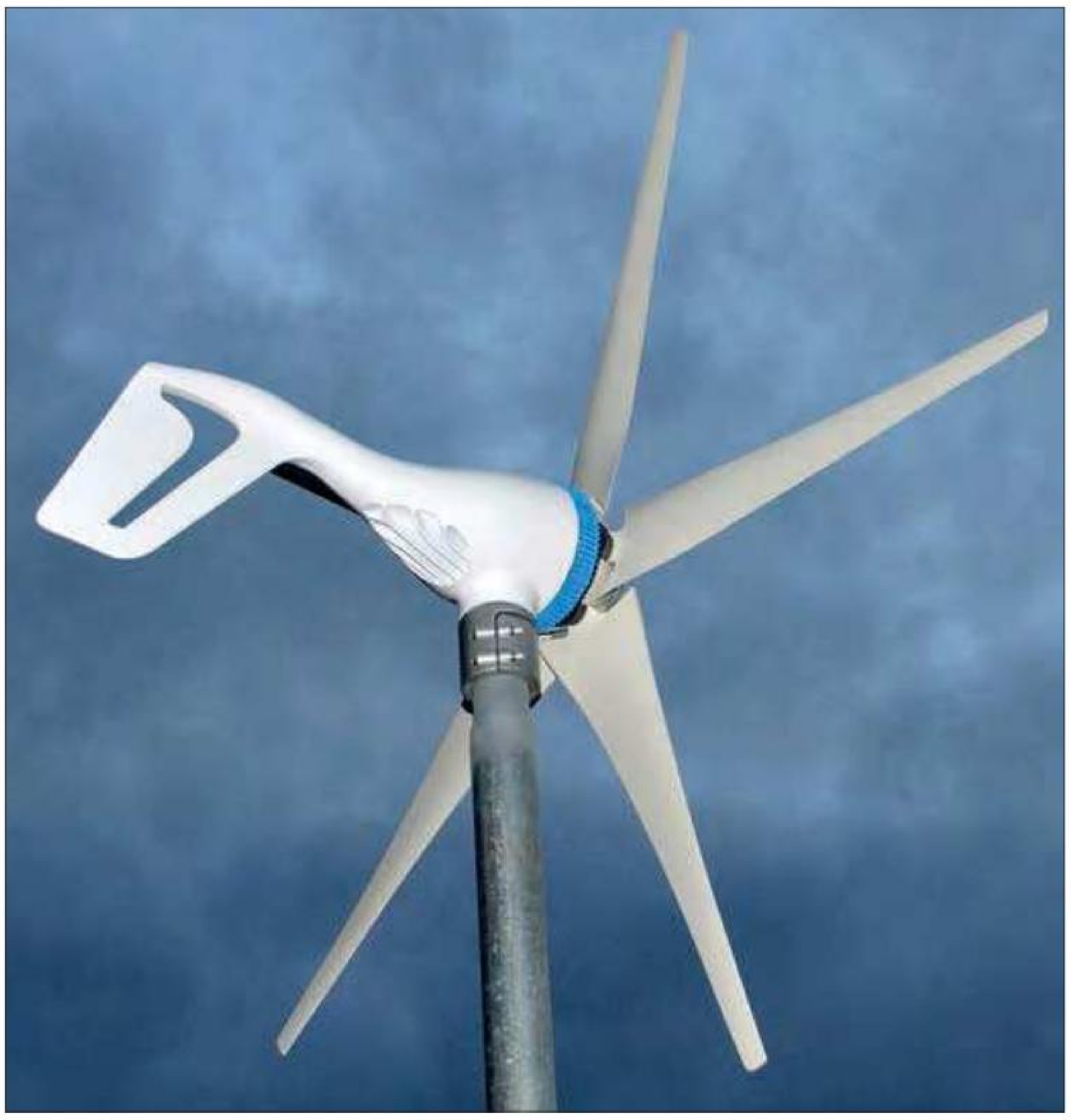


Fig.2. The assembled wind turbine mounted on a mast. Note the well-designed mast clamp that requires a 54mm diameter pipe.

The design uses a three-phase AC alternator, and the body is cast alloy. Claimed output is 300W – but more on this in a moment. Two versions are available: 12V and 24V. I used the 12V unit.

Just a note about pricing. I paid about £100 each, but at times the same turbine is listed at anywhere up to double that. The trick is to keep a good watch on prices, both on Banggood and eBay. Wind turbine prices seem to fluctuate a great deal. (Plus, new models are introduced, changed and updated at quite a rate. Don't be put off if you can't find exactly the same model shown here, or the most similar looking one is now rated, at say, '400W'.)

As stated, the unit I bought is really well made. The alternator turns on a generous bearing that can be replaced after removing a circlip. To allow the turbine to face into the wind, the whole assembly rotates on another vertical bearing. Power output is via three slip rings that use large carbon brushes.

Some assembly is required – the blades need to be bolted to the cast hub with the provided bolts and nyloc nuts. A small socket tool is provided to do this. Ensure you mount the blades in the correct orientation – recesses in the blades match the shape of the hub. The blade assembly is then attached to the alternator shaft with a large nut – again of nyloc design. The shaft nut fits within a shaped recess in the hub, so the nut is actually screwed onto the shaft by rotating the blades. To prevent the shaft from turning while doing this, the provided Allen key fits into a recess within the shaft. Note that this nut screws on a long way – ensure that it is fully home and that plenty of shaft thread is showing.

The mast mount is a well-made cast alloy design that clamps around a mast that's 54mm in diameter. This is an odd size, but if you are using 50mm pipe, some curved shims can be cut from an offcut of pipe.

There are only two question marks about the wind turbine's durability. First, the nylon blades may degrade when subjected to full sunlight, and second, while some of the fasteners are stainless steel, others are not – they're just plated mild steel. To protect these non-stainless-steel fasteners and the nylon blades, I painted them with a good quality outdoor paint.

The three-phase output needs rectification to allow battery charging. This rectification is one of the functions achieved by the electronic module that is provided with the turbine. Called the 'wind turbine controller', the module has five connections and three monitoring LEDs. The connections are the three phases from the turbine and the two to the 12V battery terminals: positive and negative. The LEDs show battery, charging and braking. Braking needs some explanation. When charge voltage exceeds a designated level, the controller slows the turbine, presumably by introducing a load across the windings.

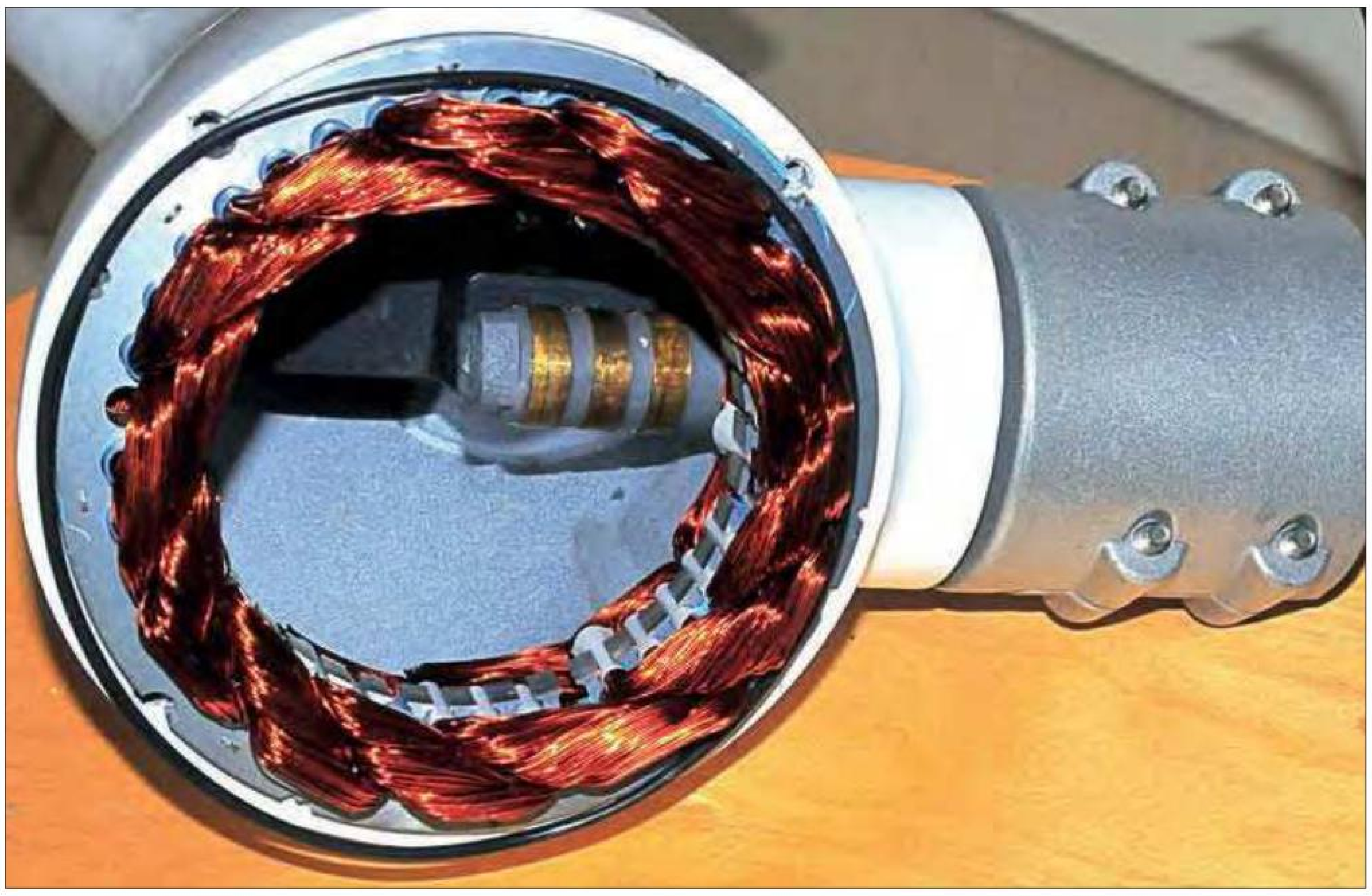


Fig.5. Inside the wind turbine – the alternator windings can be seen around the periphery, with the brass sliprings visible through the opening. The sliprings work with carbon brushes and allow the wind turbine to always swivel into the wind without winding up a connecting cable.

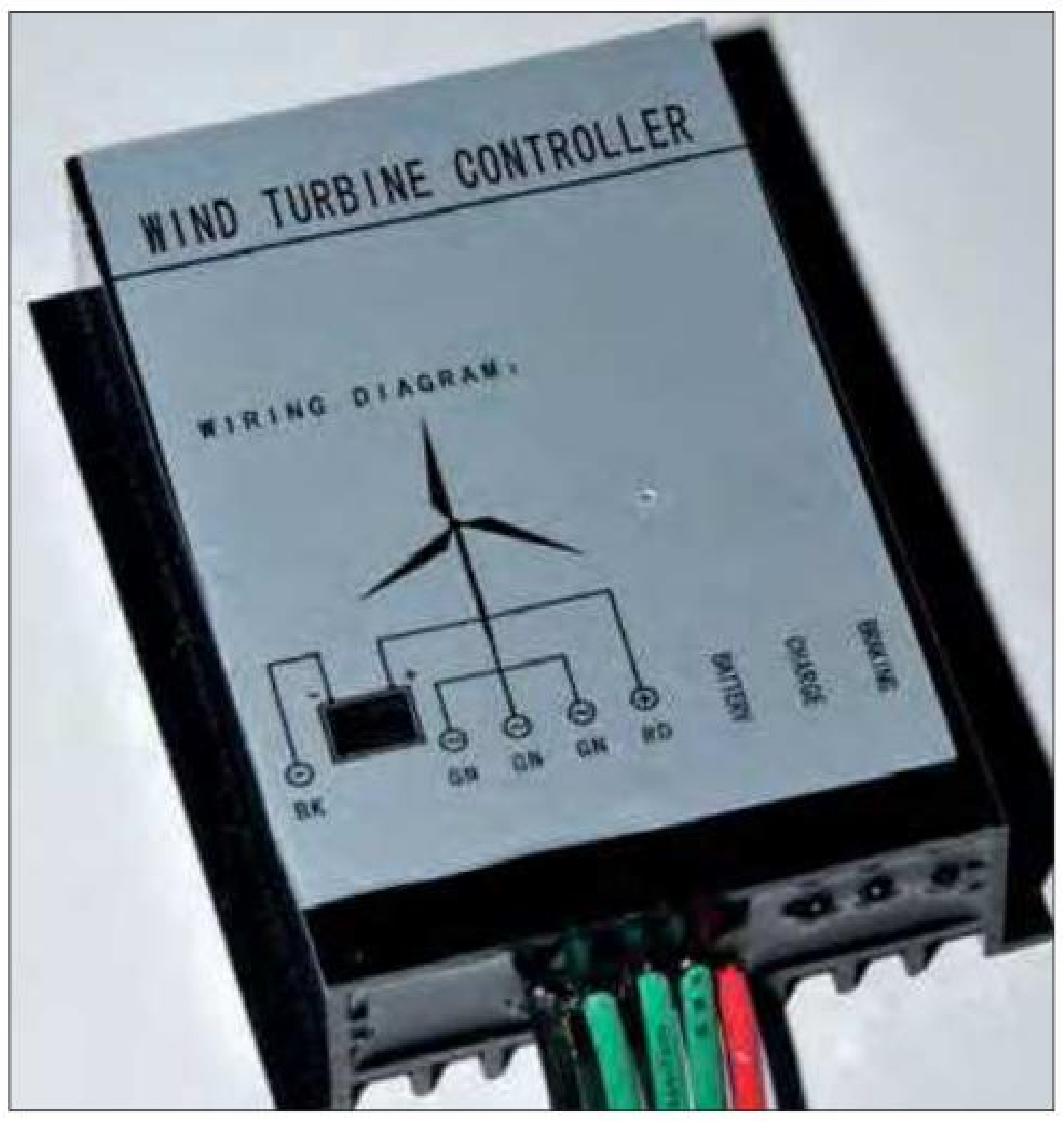


Fig.3. The controller that is provided with the wind turbine. It doesn't control charge voltage very well and has no 'boost' function, so resulting in a low output at speeds below 25km/h.

Performance in standard form

So, and I know everyone's been waiting for this with bated breath, how much power can this turbine develop? The approach that seems to best reflect reality is to connect the turbine, via its controller, to a 12V battery and monitor the charging current and voltage. To make it as fair as possible, a dead flat battery wasn't used – instead, it had a voltage of about 12.4V. The turbine was placed on a short pole that was attached to the back of a vehicle that was then driven down the road – a closed road, of course! The following data was measured:

Wind speed (km/h)	Current (A)	Voltage (V)	Power (W)
40	1.2	12.5	15
50	4.6	16.2	75
60	4.6	16.6	76

A final run was then done at 80km/h, which gave a power output of 90W. These figures are way below the claimed 300W, but I wasn't much surprised – always apply a large discount to stated wind turbine power outputs!

But two things did concern me. The first was that at 20km/h there was very little power available to charge a 12V battery. And my second concern? As the table above shows, the turbine braking seemed completely ineffective at regulating charge voltage for the 12V battery.

I then mounted the turbine on a 3-metre pole, wiring-in an LED floodlight that was able to operate on 12-24V (and so catering for the – at times – very high charge voltage). But while this worked in strong winds, in my average wind conditions, the light mostly stayed off.

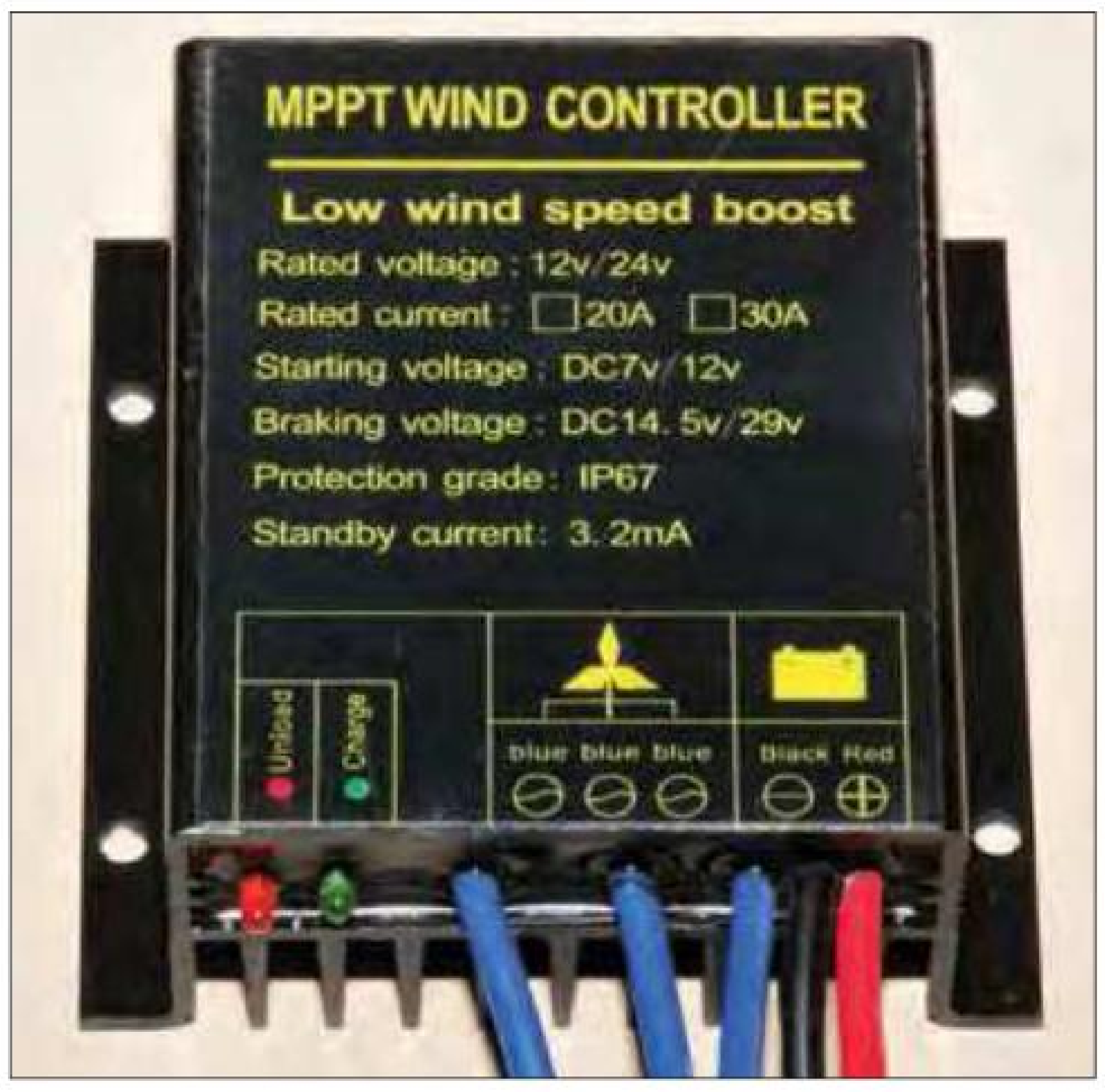


Fig.4. The upgrade controller incorporates an effective boost function, giving useable 12V battery charging output from about 20km/h. The device also better brakes the turbine, limiting charge voltage to about 13.9V (not the 14.4V written on the box).

Boost converter

Hmmm. I was impressed by the engineering and construction of the wind turbine (it's certainly much cheaper than trying to make one of this size yourself), and I wasn't even much fussed by its relatively low output in strong winds. But to make it viable for me, it needed to have a better output at wind speeds around 20km/h. So, what about adding an auto-regulating step-up converter? Braking could then be controlled by a voltage-sensing device that switched in a large resistor.

By good fortune, Banggood had beaten me to it and has available the '12/24V MPPT Dual USB Wind Power Controller Auto Work Wind Generator Voltage Booster Controller Wind Controller PWM'. It's rated for 500W (easily enough) and so I bought the 12V version (£24) and did some testing. (Incidentally, the device has no USB functions at all, so I am not sure how that crept into the description.)

The good news is that, at low wind speeds, the new control module effectively doubles the output of the wind turbine! For example, at around 20km/h wind speed, and charging the 12V battery, the output had previously been about 0.5A. With the new boost converter, this rose to about 1A. Furthermore, the new module is much more effective at regulating turbine speed (and so voltage output), fiercely braking the turbine at 13.9V (not the 14.5V written on the box) and so preventing any higher charge voltage.

Final set-up

My final set-up is this. The turbine is mounted on a 6-metre pole that is bolted to a well-seated fence post. At the base of the pole is located a 12V, 26Ah sealed lead acid battery. (I have ended up with a number of these batteries, but if I didn't have them, I would use a discarded car battery. Many car batteries are thrown away when they still have plenty of life left in them for an application like this.)

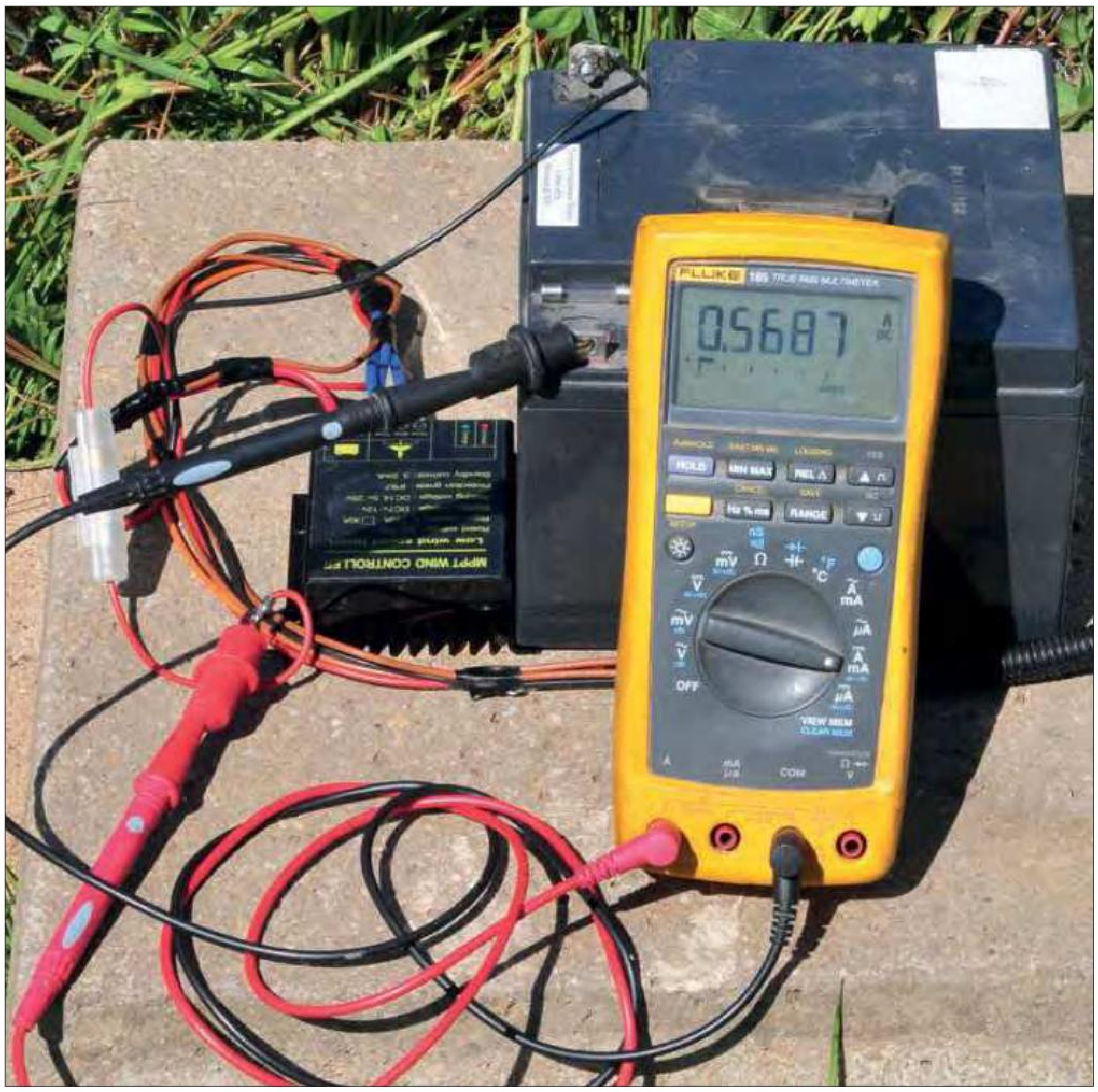


Fig.6. Charging a 12V SLA battery in a 15km/h wind. Charge current is just over 0.5A – more than enough to keep the battery charged for its occasional use in powering LED floodlights. Note the fuse at left – this should be placed in circuit between the battery and the controller / load.

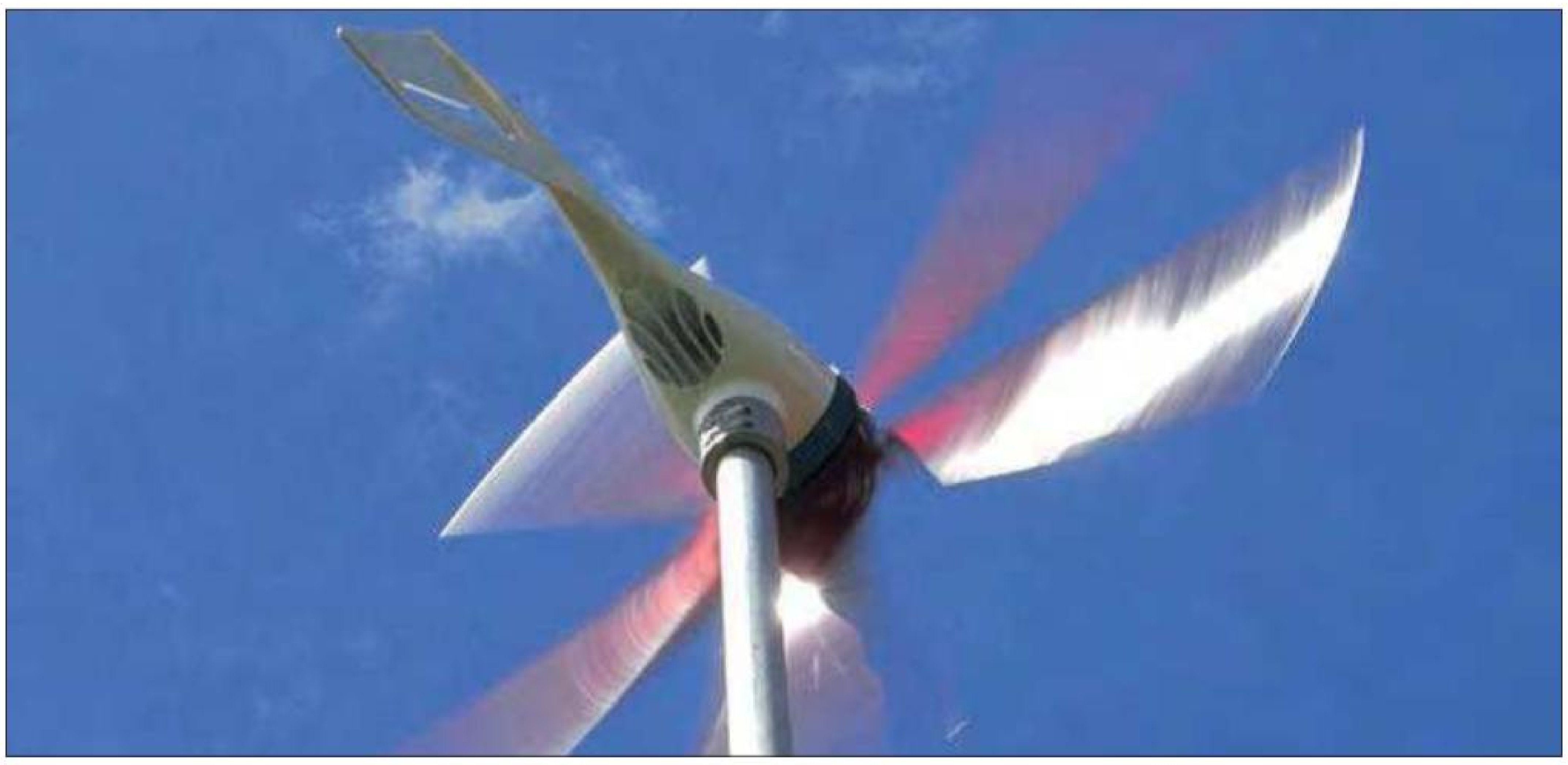


Fig.7. What can't be shown in the pics is the graceful elegance of the whirling blades. The turbine is quiet, developing only a faint *whhhsssssh* noise at speeds over 30km/h. Unlike huge ones used for grid generation, this turbine is a high-speed device.

Adjacent to the battery is the boost controller module. Mounted on the pole are two 10W LED floodlights (also, of course, from Banggood). These lights are powerful, well-sealed and use stainless steel fittings. A manual weatherproof light switch is mounted on the pole. The floodlights illuminate a vegetable garden that is on land where we are building a new house, but there's not yet mains power on-site. The lights are seldom used for more than an hour at a time and so the battery has plenty of capacity, even if the wind doesn't blow for a while.

And the other wind turbines I have bought? One will power a battery back-up shed alarm, and the other – well, to be honest, I haven't yet quite decided.

Conclusion

It's not going to power your house but if you're after a relatively low-cost wind turbine that – especially when equipped with the boost module – has a useable output, this is one to go for.

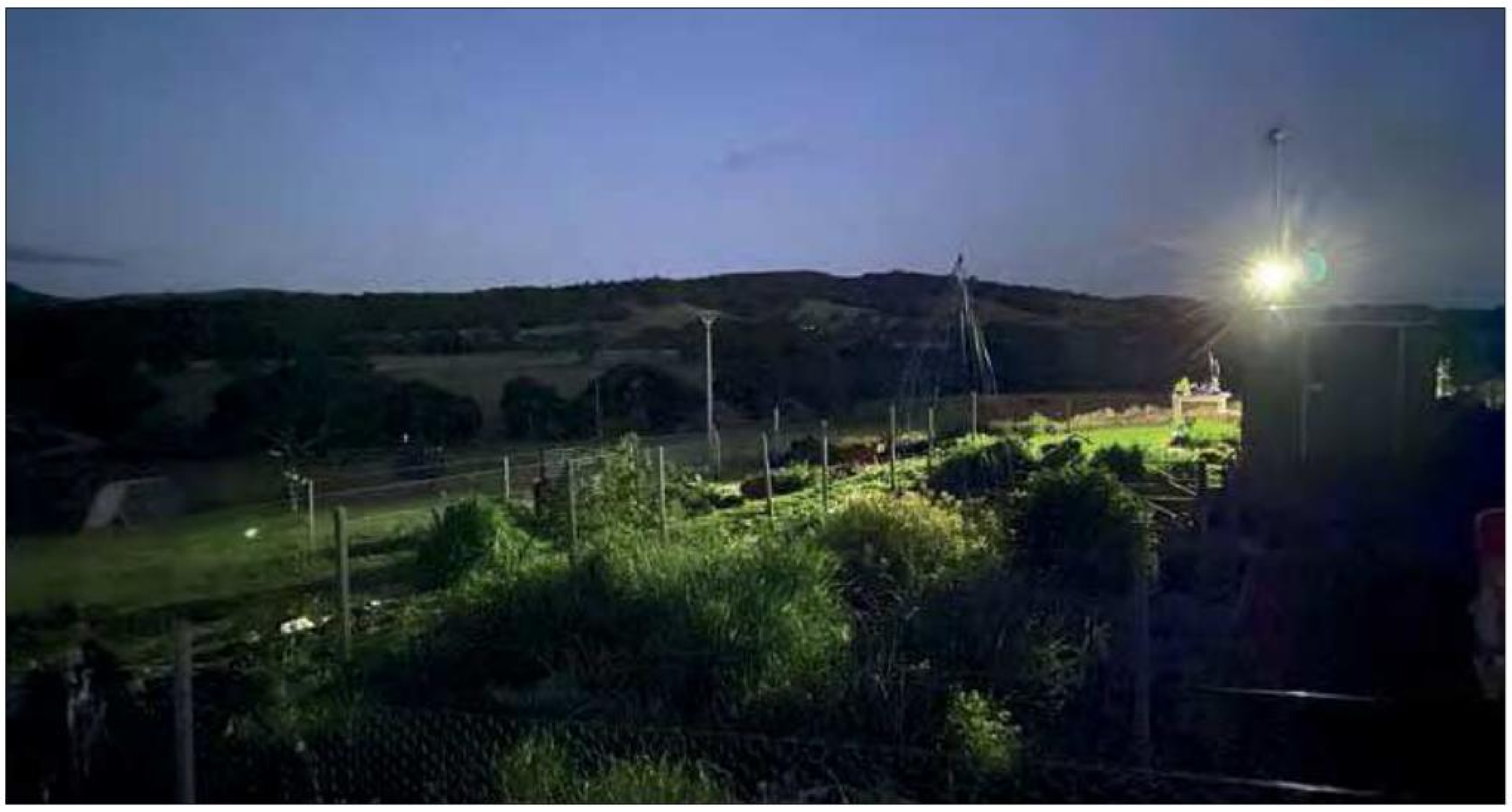


Fig.11. The vegetable garden, lit by wind power.

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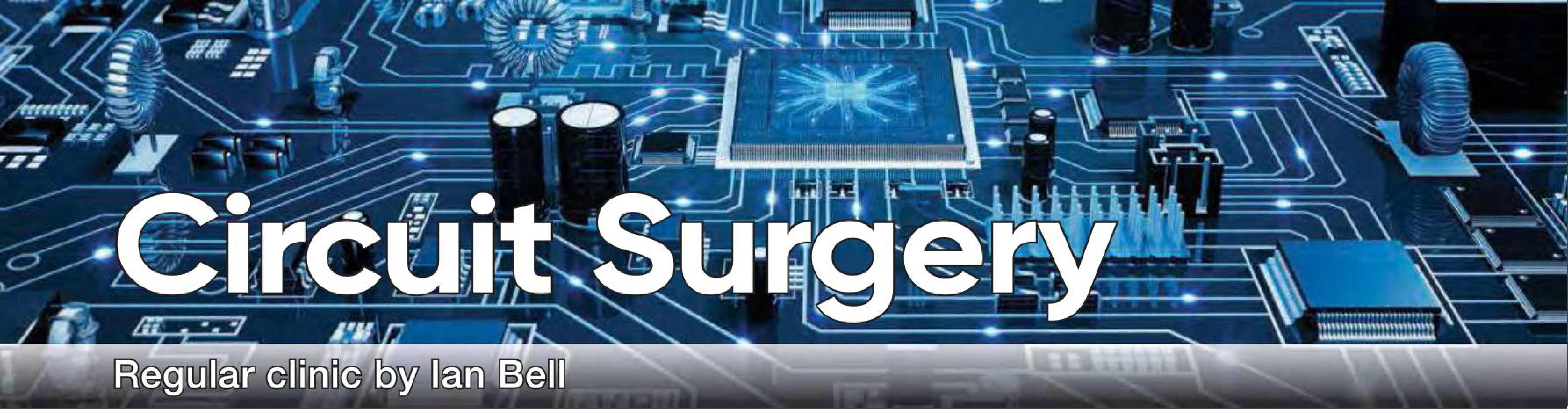

Circuit Surgery

Regular clinic by Ian Bell

Royer oscillators

Recently, user Frostyjams posted a question about the Royer oscillator on the EE Web forum. We will not address the specific question asked – there is a reference to schematics which are not available at the time of writing; however, this is an interesting circuit so we will take a look it in more general terms. The Royer oscillator is also referred to as the 'Royer converter' because it is commonly used in inverter power converters which generate relatively high AC voltages from a DC supply (of course, the AC output can also be rectified to give DC-to-DC power conversion). There are also several similar circuits which can be used for the same purpose.

A common use of Royer (or similar) converters has been for generating the high voltages needed for display backlighting using Cold Cathode Florescent Lamps (CCFL). However, use of CCFL backlighting has been decreasing for the last decade as LED-based approaches take over. Nevertheless, there are a variety of reasons why step-up voltage converters might be needed where a Royer converter, or similar circuit might be considered.

Safety warning

This article will discuss the principles of the Royer converter, including some issues relating to simulation. We are not presenting a complete design (project), but of course designs can be found elsewhere. Anyone interested in building these circuits must be aware that (depending on the design) they may be capable of producing dangerous output voltages and high levels of heat dissipation leading to hot components. There is a risk of electrocution and burns, so appropriate safety precautions must be taken when working with such circuits.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*.
The examples and files are available for download from the *PE* website.

Origins of the Royer oscillator

The Royer converter was first described by GH Royer in 1954. A basic Royer oscillator circuit is shown in Fig.1. It is based around a transformer with multiple windings driven by two transistors. The oscillator is formed by driving the centre-tapped primary winding L1-L2 and receiving feedback via a relatively small centre-tapped secondary winding L3-L4. The oscillation will occur with just these two windings, but for obtaining a step-up output voltage a third winding is required (L5) – this is a secondary of the transformer that can deliver a stepped-up output voltage. The voltage induced in the secondary depends on the supply voltage (V_{CC}) and the transformer turns ratio from winding L1-L2 to L5.

In order to use the transformer correctly in the Royer oscillator it is necessary to know which way round the terminals are connected. This is indicated by using dots on the device and on the schematic symbols – these are known as 'phasing dots'. The dotted terminals have the same instantaneous voltage polarity during transformer action. For example, when a dotted primary is being driven by the positive half of the AC cycle (or positive voltage pulse) a dotted secondary will have a positive polarity with respect to its non-dotted terminal. During this positive cycle the current will flow into the dotted primary terminal and out of the dotted secondary.

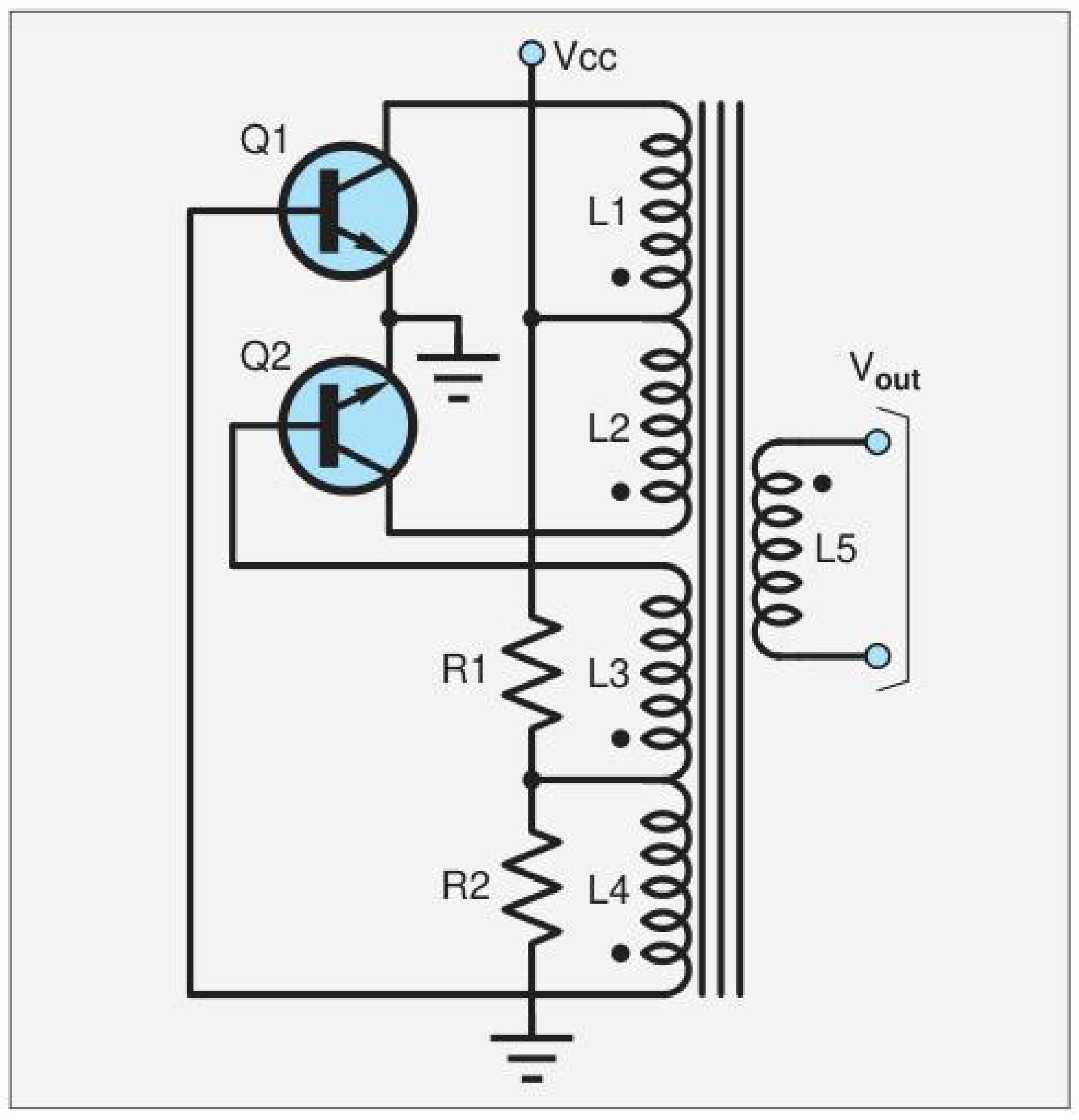

Fig.1. Basic Royer power converter circuit.

Magnetic saturation

Operation of the Royer oscillator involves magnetic saturation, so it worth defining what we mean by this. Applying an external magnetic field to a magnetic material magnetises it. Magnetic saturation occurs when an increase in an applied magnetic field cannot further increase the magnetisation of the material. This happens in some types of material, particularly ferromagnetic materials such as iron. In these materials there are microscopic domains, which act like very small magnets that can change their direction of magnetisation. In the presence of an external magnetic field the domains have a tendency to align with the applied field. The stronger the field the more aligned the domains become; however, there is a limit to this process after which any further increases in the applied magnetic field will not cause more domain alignment (magnetisation). At this point, magnetic saturation has occurred.

If the core material of an inductor exhibits saturation, then the inductor will become nonlinear at currents which approach or exceed the saturation point. This means that the inductance will vary with the current flowing through the inductor (ideally, the inductance of an inductor does not change with the current through it). The inductance reduces as the core enters saturation; and this will also reduce coupling between

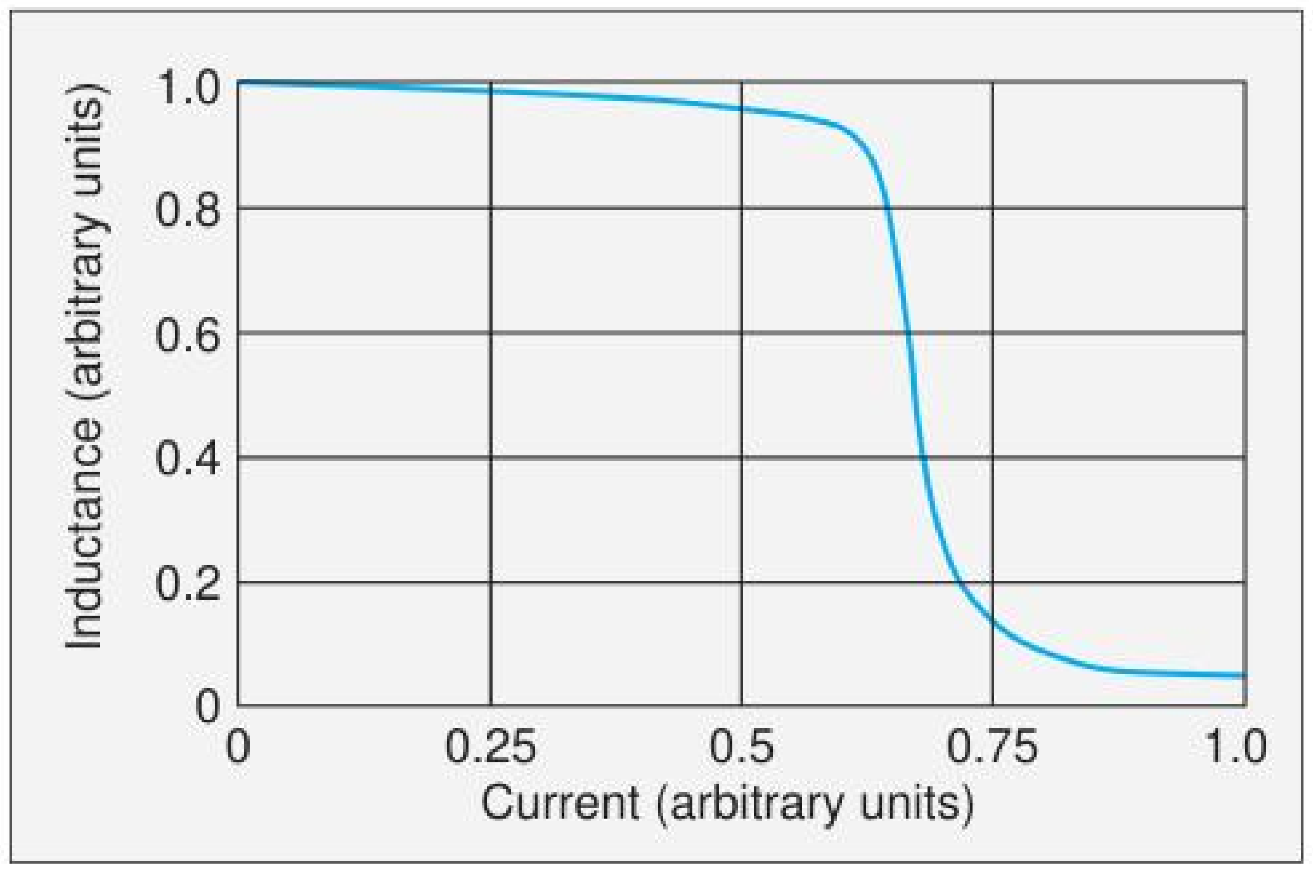

Fig.2. Example of typical inductance vs current curve for an inductor exhibiting hard saturation. The specific shape, inductance and current values will depend on the size of the inductor and core material.

windings in a transformer. The shape of an inductance vs current graph varies depending on the properties of the core material. An example is shown in Fig.2 – this shows a characteristic referred to as ‘hard saturation’, where the inductance reduces rapidly above a certain current level. In most applications, saturation is avoided as the reduction in inductance may lead to damaging increases in current, waveform distortion, or poor efficiency. However magnetic saturation is exploited in some applications, and it plays a part in the operation of the Royer oscillator.

Waveforms and frequency

Royer circuit oscillation is ‘square wave’ in nature rather than sinusoidal because the transformer is driven into saturation (an appropriate transformer, with suitable core material, must be used to achieve efficient operation). In mains power supplies the input to the transformer primary is a 50Hz or 60Hz sinewave. For DC-to-DC converters, neither a sinewave nor a frequency as low as this has to be used. Higher frequencies enable smaller transformers to be used, and if the frequencies are above the audio range (>20kHz) then they will give silent operation (you may hear a hum or whine from power circuits operating in the audio range).

Pulsed (square-wave) inputs to a transformer (or other inductor) are commonly used in modern switching power supplies because they are relatively easy to generate using control logic. This logic often uses pulse modulation (switching pulses on or off, or modifying their length) for feedback control of the output voltage as the load varies. Of course, such converter circuits deliver better performance than the basic Royer oscillator converter (which does not regulate the output), but Royer oscillators (or similar circuits – see later) can be used in conjunction with modern switching regulators to provide a more stable output voltage. This was a common approach in the heyday of CCFL backlighting.

Circuit operation

The resistor network (see Fig.1) provides bias and ensures that one of the transistors switches on and the circuit starts oscillating when power is applied. When the circuit powers up, real-world asymmetry will result in one of the transistors switching on faster than the other (the two halves of a real circuit will never be exactly the same, despite the symmetrically designed structure). The circuit has a ‘bistable-type’ behaviour, with the transistors switching on and off out of phase with one-another, with a duty cycle of 50%.

An advantage of the Royer circuit is that the transformer is directly part of the oscillator, so it uses relatively few components to achieve a step-up converter (compared with using separate oscillator and driver stages). However, the circuit has quite a few issues, which we will discuss later.

Transistor operation

Appropriate transistors should be used, which must have high gain (h_{FE}), low saturation voltage $V_{CE(sat)}$, low on-resistance ($R_{CE(sat)}$) and high collector-base breakdown voltage. Transistors specifically designed for high-current switching applications should be used. As noted above, the transistors alternate being on and off and one will switch on first at power up. So, we can use the assumption that one transistor has just switched on as a starting point for describing circuit operation. If we assume Q1 switches on first then L1 will have voltage across it with the dot end positive, and by transformer action there will be voltages produced on the L3-L4 secondary with polarity corresponding with the dotted ends of the windings. Thus, Q1’s base will be driven positive – turning the transistor on more – this is positive feedback, which will ensure definite switching.

After Q1 switches on, the magnetic flux in the core will be increasing (the rate of change can be found from Faraday’s law, which relates the rate of change of magnetic flux to electromotive force). However, after some time in this state the transformer will saturate, that is the magnetic flux with stop increasing, at which point the majority of the transformer action will stop, and with it the base current to Q1. With the base current removed, Q1 will turn off, causing

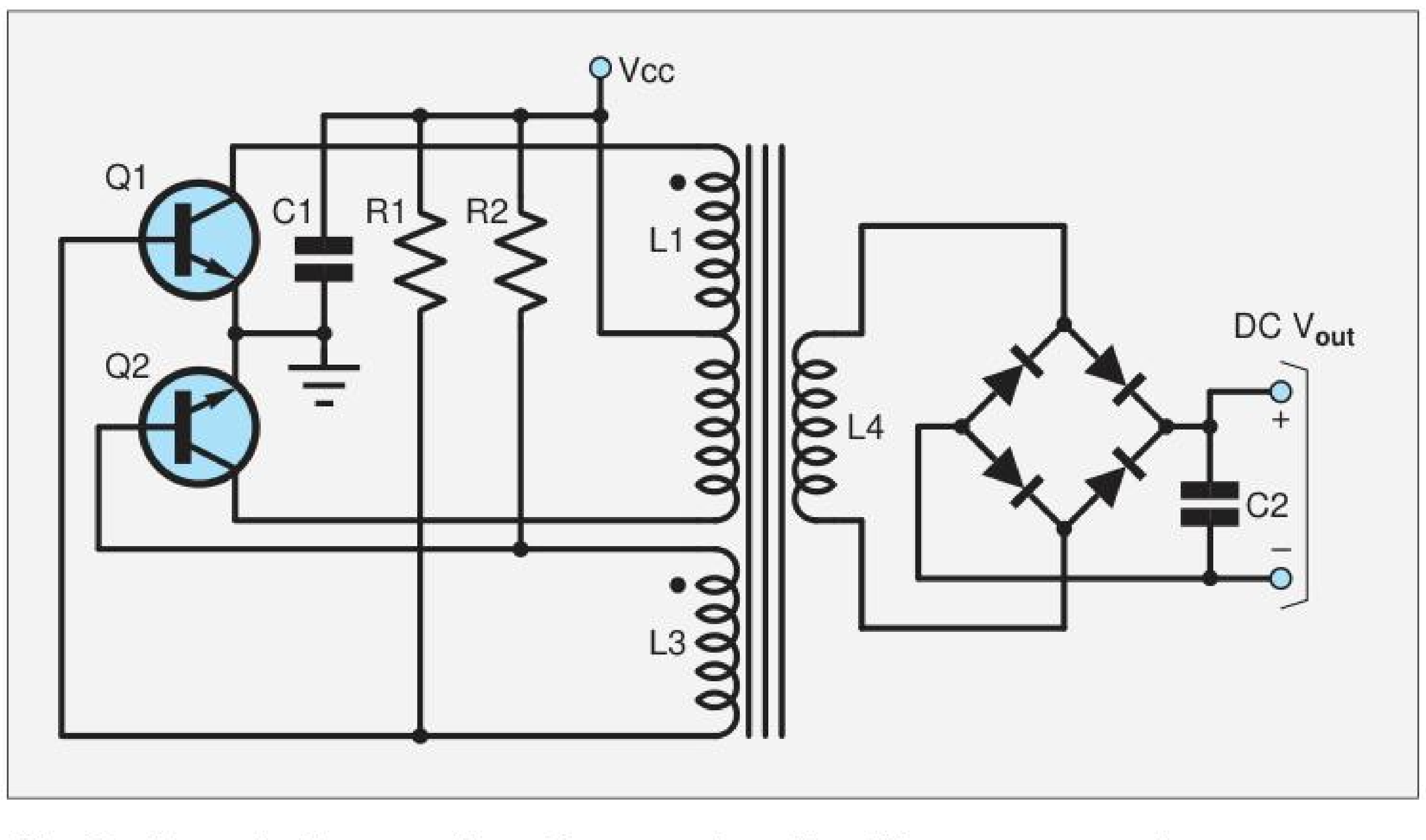

Fig.3. A variation on the Royer circuit with an example secondary side circuit.

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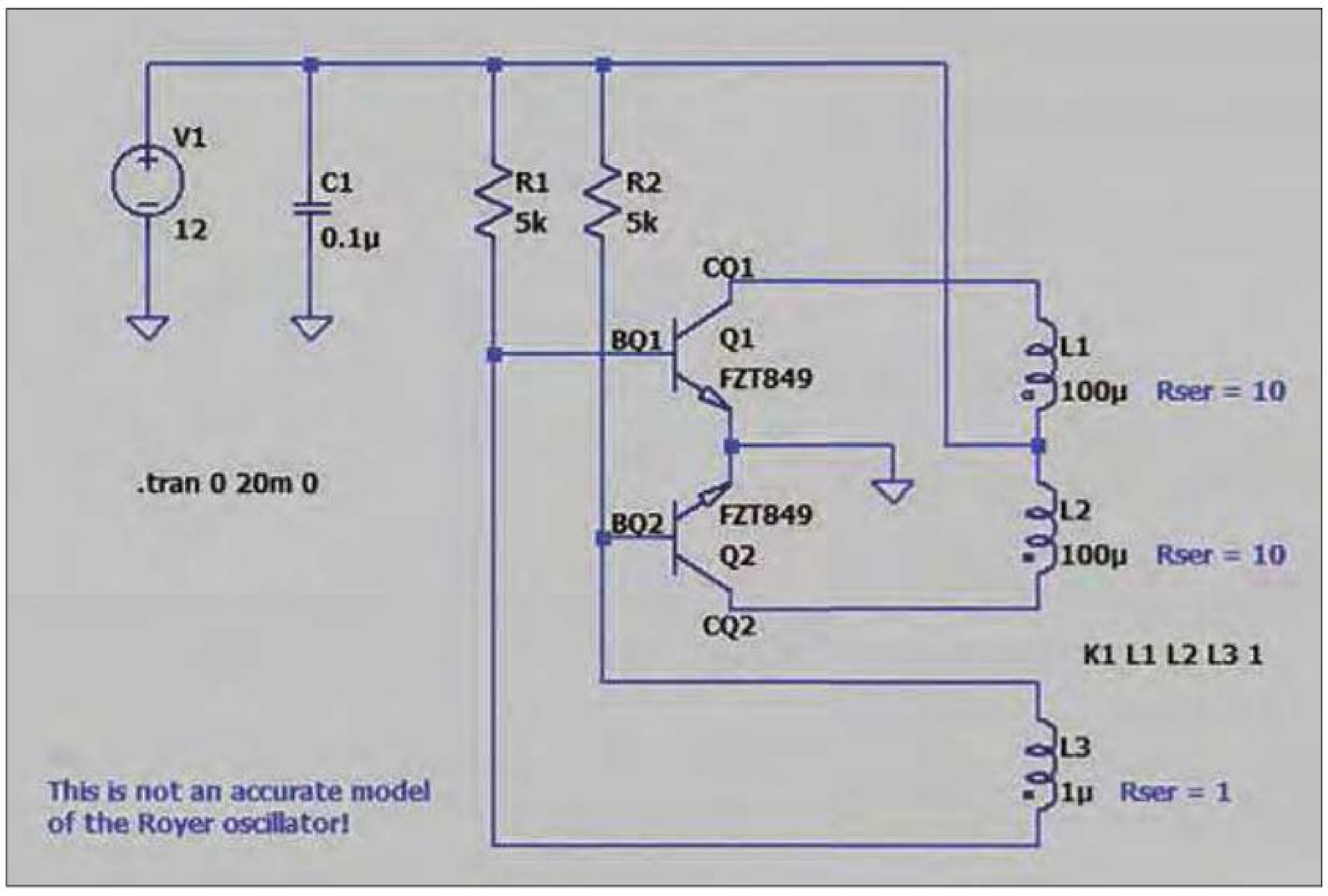


Fig.4. LTspice Royer oscillator schematic (which is not an accurate model).

its collector current to drop. This reversed voltage change will, via the remaining transformer action, produce a positive voltage at Q2's base, turning it on, and again the positive feedback action will push this switching action, further turning Q2 on.

As Q2 turns on the resulting change of voltage polarity on the primary (check the dots on the schematic) will cause the transformer to first come out of saturation and then saturate with the flux in the opposite direction to when Q1 was on. When Q2 saturates it will switch off, in the same way Q1 did, and consequently Q1 will start to switch on and the cycle will repeat. Thus, we have oscillation. The frequency of oscillation depends on the transformer core's cross-sectional area, number of turns in the primary, its magnetic properties (saturation flux), and the supply voltage. This makes it relatively difficult to set a precise frequency.

There are a number of possible variations of, or additions to, the basic Royer circuit in Fig.1. These include the addition of diodes to protect transistors from voltage spikes and variations of the bias and secondary feedback circuit. An example of this is shown in Fig.3 – this circuit does not need a centre-tapped feedback winding. The circuit in Fig.3 includes a supply decoupling capacitor (C1) – supply decoupling is generally good practice, particularly with switching circuits such as this which may experience large transient current demands. Fig.3 also shows a full-wave rectifier circuit and smoothing connected to the secondary – this is just an example – different secondary circuits can be used depending on the application.

Royer simulation

We often simulate circuits for *Circuit Surgery* articles, but the Royer oscillator is challenging to simulate accurately. However, it is worth looking at a couple of the issues involved. Fig.4 is an LTspice schematic of a Royer oscillator based on Fig.3. The component choices are somewhat arbitrary – simulating this is not going to be realistic, so it really isn't worth worrying about it too much.

To create a transformer in LTspice we need to define a mutual inductor (add a mutual inductor component to the netlist), which is done by adding the netlist line for a mutual inductor as text to the schematic. The syntax of the mutual inductance statement is:

```
Kxxx L1 L2 [L3 ...] <coefficient>
```

This is a name starting with `K`, followed by the list of inductors which are coupled together (the windings of the transformer), followed by the coupling coefficient. For ideal transformers, the coupling coefficient is `1`, but it can be set in the range `0` to `1` to model transformers where not all of the magnetic flux perfectly links the coils. Here we use `1` to keep things simple.

The results of simulating the circuit in Fig.4 are shown in Fig.5. Note that there are oscillations, but they take a long time to get started. When simulating oscillators like this, start-up is often a problem – some circuits do not oscillate at all in simulation. The reason in this case is the perfect symmetry of the simulated circuit, something which does not occur in real circuits – earlier we assumed one of the transistors switched on first, which started the oscillation, but this may

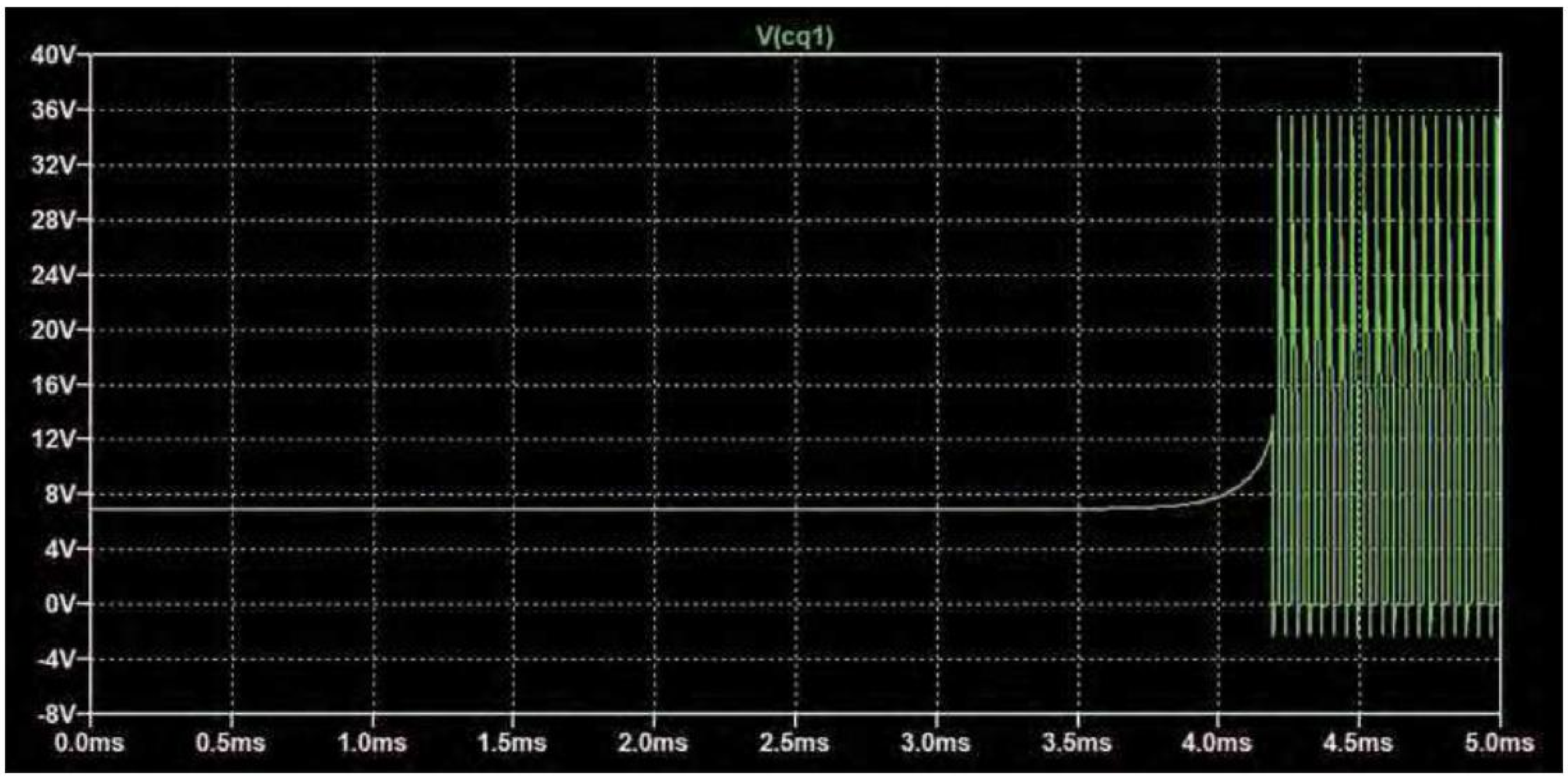


Fig.5. Simulation results for the circuit in Fig.4.

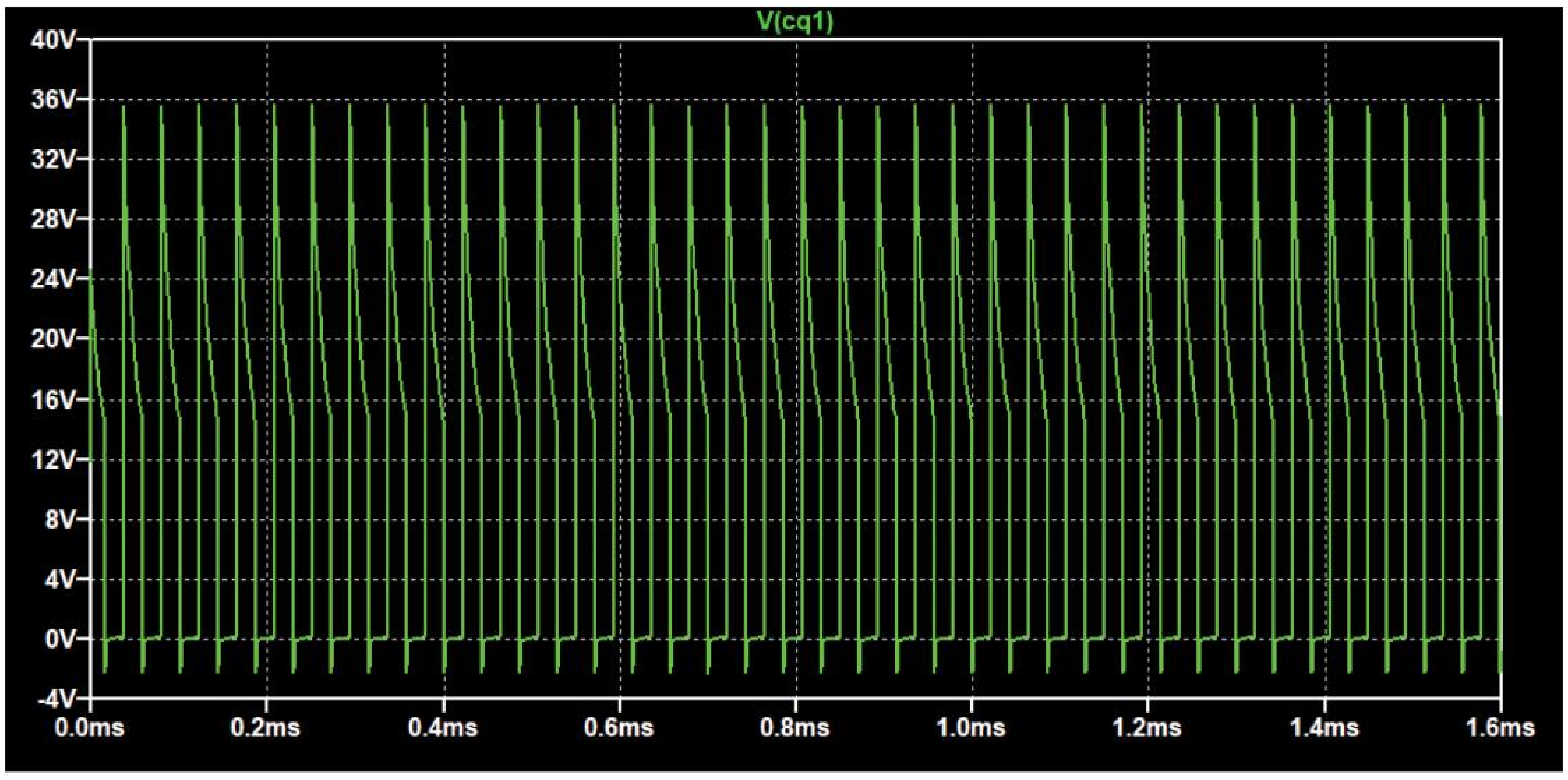


Fig.6. Setting initial conditions can help start oscillator simulations.

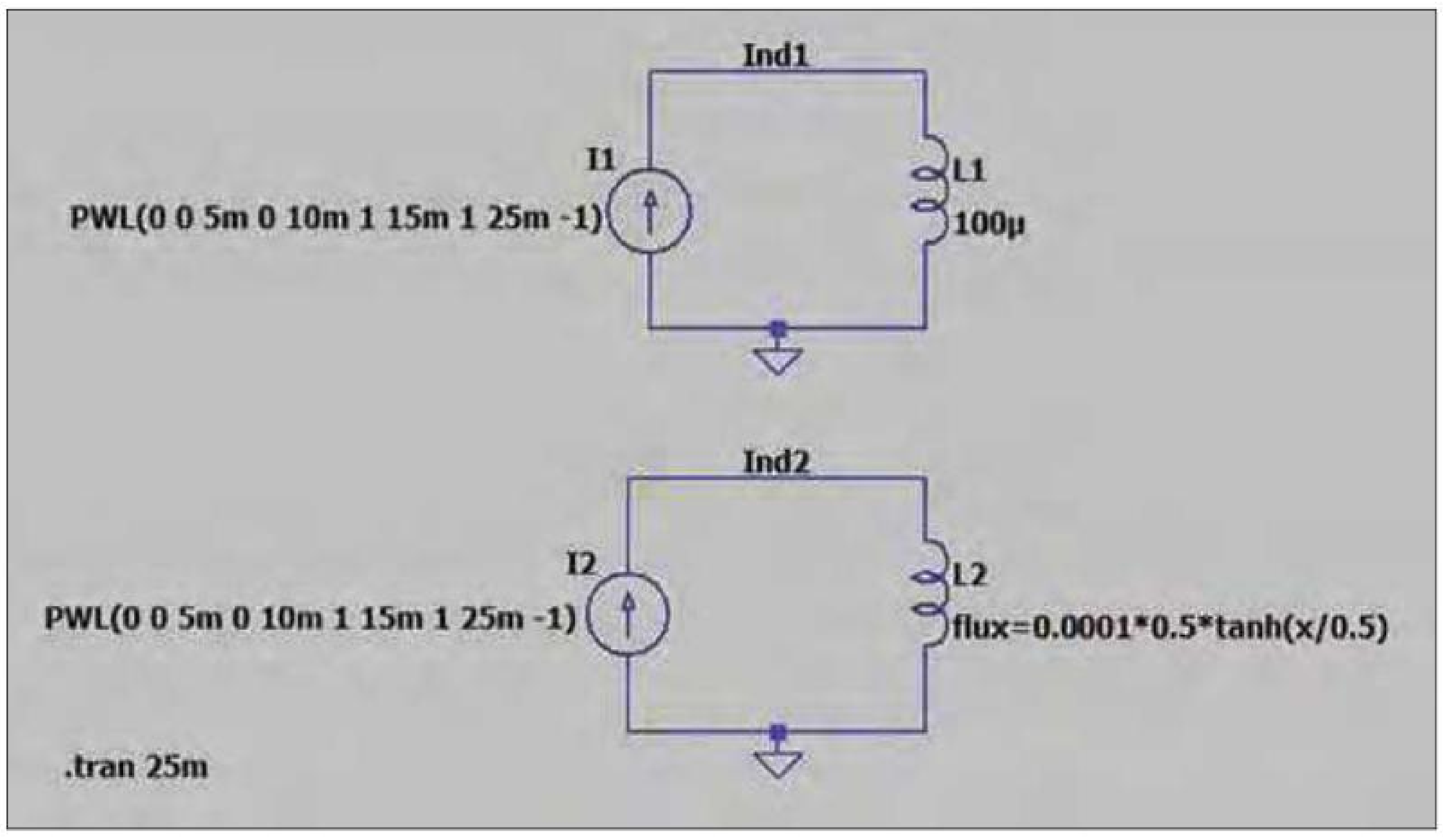

Ind1
I1
PWL(0 0 5m 0 10m 1 15m 1 25m -1)
L1
100µ
Ind2
I2
PWL(0 0 5m 0 10m 1 15m 1 25m -1)
L2
flux=0.0001*0.5*tanh(x/0.5)
.tran 25m

Fig.7. LTspice schematic to demonstrate inductor saturation.

not happen in the simulation with two identical transistor models. For the simulation, numerical differences between node calculations may be sufficient to start the simulation, but probably not in a realistic way.

Forcing simulator oscillation

Oscillation start-up in symmetrical oscillator circuits can be achieved by introducing asymmetry in the circuit, or by forcing the circuit voltages to initialise in a state that will start the oscillation. For the first approach, we could change component values – for example, in this circuit, setting slightly different resistor values may work.

For the second approach we can try the `.IC` and `.NODESET` SPICE directives. These control the DC initial conditions which LTspice calculates at the start of every simulation, and are used to determine the starting point for transient simulations. The `.IC` directive forces the initial voltage at the start of the simulation, whereas `.NODESET` is more of a hint to the simulator during its initial calculations. Although use of `.IC` requires caution because it can give misleading results, it can be useful for starting oscillators if `.NODESET` does not solve the problem. For the circuit shown in Fig.4, consider:

```
.IC V(bq1)=0.6  v(bq2)=0
```

This forces the base voltages at the start of the simuation to a situation where Q1 is on and Q2 is off, which will start the oscillation immediately, as shown in Fig.6. The statement is added to the schematic using the '.op' SPICE directive button.

Simulating transformer saturation

It would be easy to assume that Fig.6 is a useful result – it shows a 'spikey' square wave oscillation, which is what we might expect from a Royer oscillator. However, we need to be very cautious as there is a very significant factor lacking from the simulation model, which was a key element of our description of the circuit's operation – that is saturation of the transformer. The inductors in the simulation are close to ideal (apart from the series resistance specified) and so do not exhibit saturation, so it is not safe to assume the results are realistic.

It is reasonably straightforward to include saturation of individual inductors in LTspice. This is done by replacing the normal inductance value on the schematic with a mathematical expression for flux to create a behavioural inductor (known as the Arbitrary Inductor model). The most basic form of the expression is:

```
flux=L*Is*tanh(x/Is)
```

Here, `L` is the inductance in henries (when not saturated), `Is` is the saturation current in amps and `x` is the inductor's current (referred to as a 'special keyword' in LTspice documentation). `tanh` is the hyperbolic tangent function. Thus, for an inductor of 100µH and a 500mA saturation current, the expression above becomes:

```
flux=0.0001*0.5*tanh(x/0.5)
```

This example is used in the LTspice schematic in Fig.7, along with a standard inductor of 100µH. This example is to illustrate the behaviour of LTspice inductor models and does not represent specific real components. The flux expression can also be more complex to model more details of the inductor saturation; for example, sharpness of the current-inductance curve.

The piecewise linear (PWL) voltage sources used in the circuit in Fig.7 create a current into the inductors which is either constant or changing at a constant rate of ±200A/s (1.0A in 5ms) – see the top trace on Fig.8. The characteristic equation of an inductor – the relationship between current through (*i*) and voltage across it (*v*) is:

$v = L\,di/dt$

Here, *L* is the inductance. The term *di/dt* is a differential, which represents the rate of change of the current (*i*) with time (*t*). Passing a current through an inductor results in a voltage

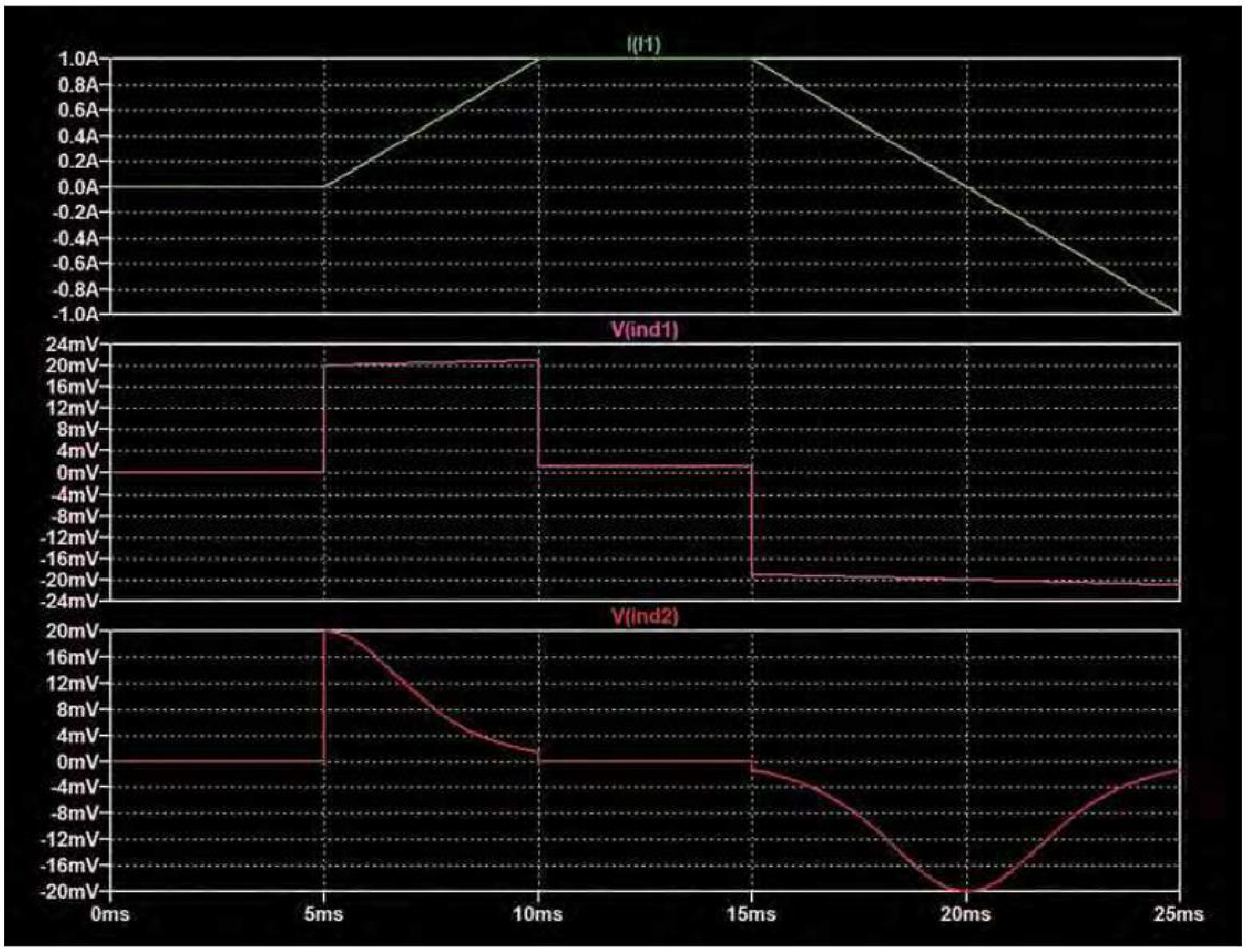


Fig.8. Simulation results from the circuit in Fig.7.

across the inductor that is proportional to the rate of change of the current.

The voltage for the standard inductor model in the simulation is shown in the middle trace in Fig.8. When the current is constant (either at 0 or at 1.0A) the inductor voltage is zero. When the current is changing at ±200A/s the voltage across the inductor is 100µH × 200A/s = 20mV, as given by the above equation, with the polarity of the voltage dependent on the direction of change of the current.

The behaviour of the inductor with saturation is shown in the bottom trace in Fig.8. It is obviously very different from the middle trace. The current-voltage-inductance equation still applies, but the inductance decreases with increasing current – as shown in Fig.2, but not necessarily following exactly the same curve. The decrease in inductance with increasing current results in lower voltages at higher currents – note, for example, the peak in negative voltage as the decreasing current passes through zero at 20ms in Fig.8.

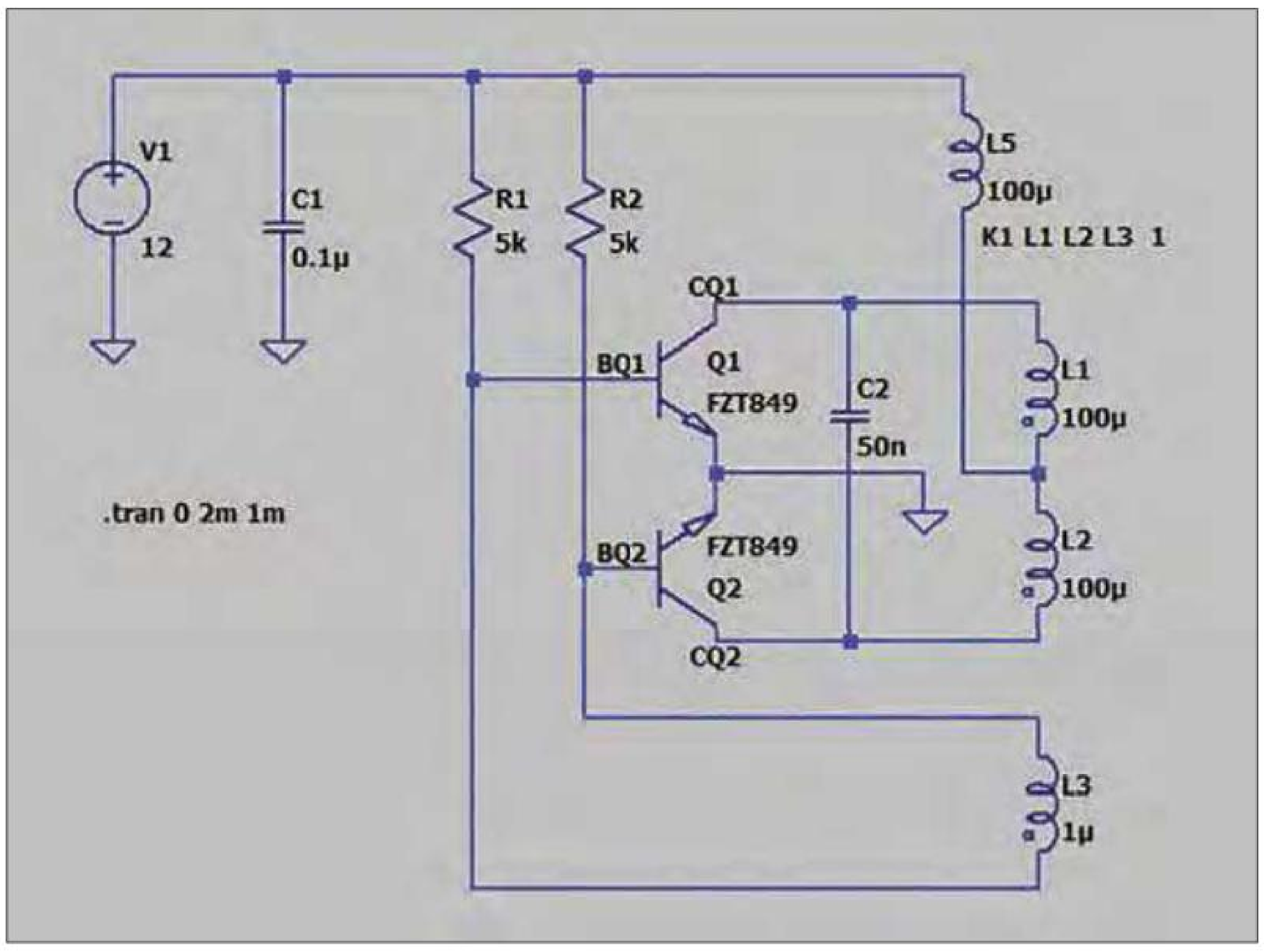


Fig.9. Baxandall oscillator LTspice circuit used to produce illustrative waveforms.

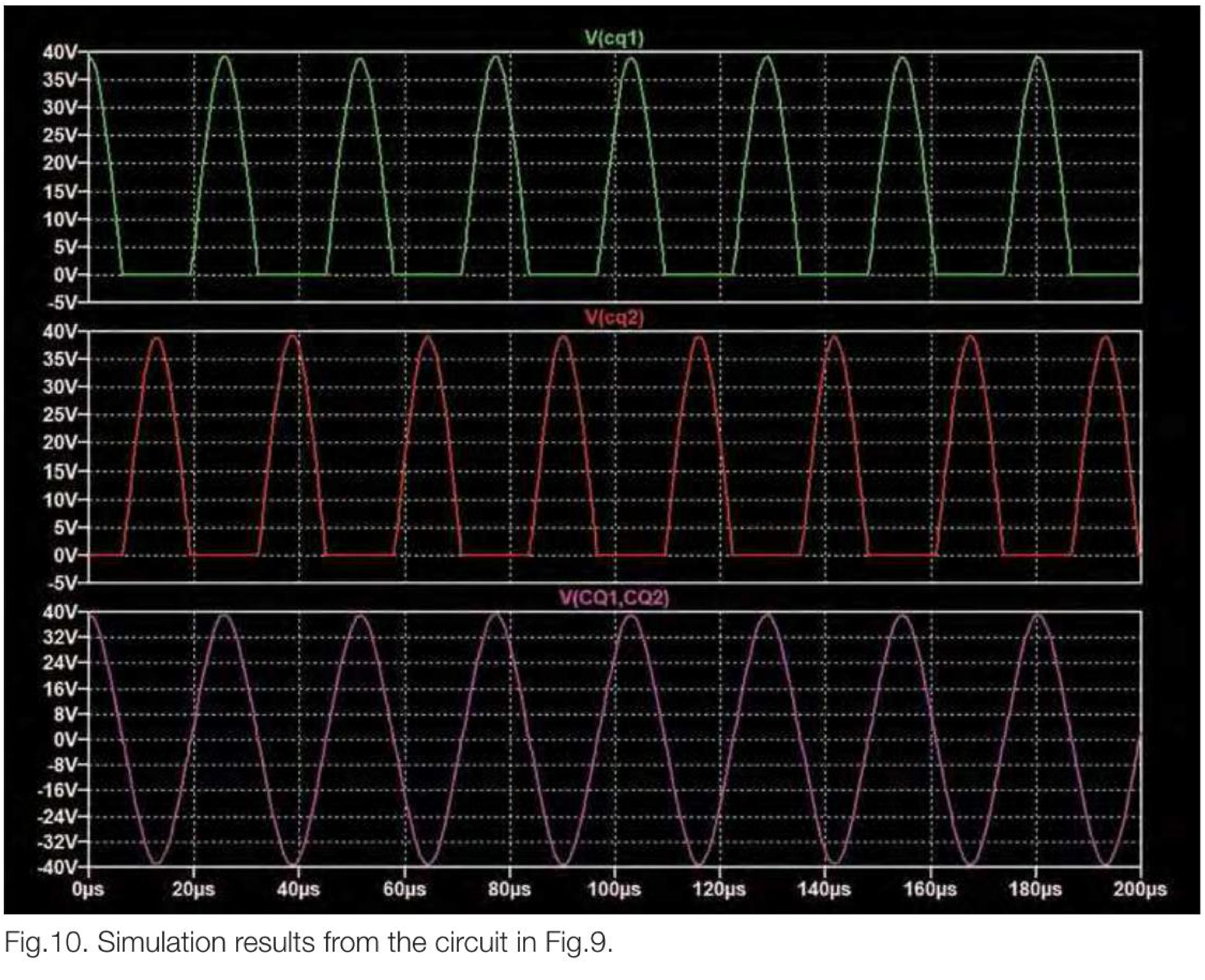


Fig.10. Simulation results from the circuit in Fig.9.

Simulation limitations

Unfortunately, the Arbitrary Inductor model does not cover all aspects of inductor saturation – specifically saturation hysteresis. Another approach can be used, which is based on the Chan model (named after John Chan *et al.* who published it in the *IEEE Transactions on Computer-Aided Design*, Vol. 10. No. 4, April 1991). This model is also built into LTspice but requires several magnetic parameters to be set for the core (in a similar way to the Arbitrary Inductor model, the list of parameter values is entered in place of the normal inductance value), so you need to know these values to use it. Furthermore, the LTspice Chan model does not support mutual inductors, so cannot be used in a straightforward way for transformers. More comprehensive transformer models exist but typically require complex equivalent circuits to represent the transformer's behaviour. Thus, we conclude our simulation discussion without a detailed model of the transformer in Fig.3, but with some insights into the difficulties.

Drawbacks of the Royer oscillator

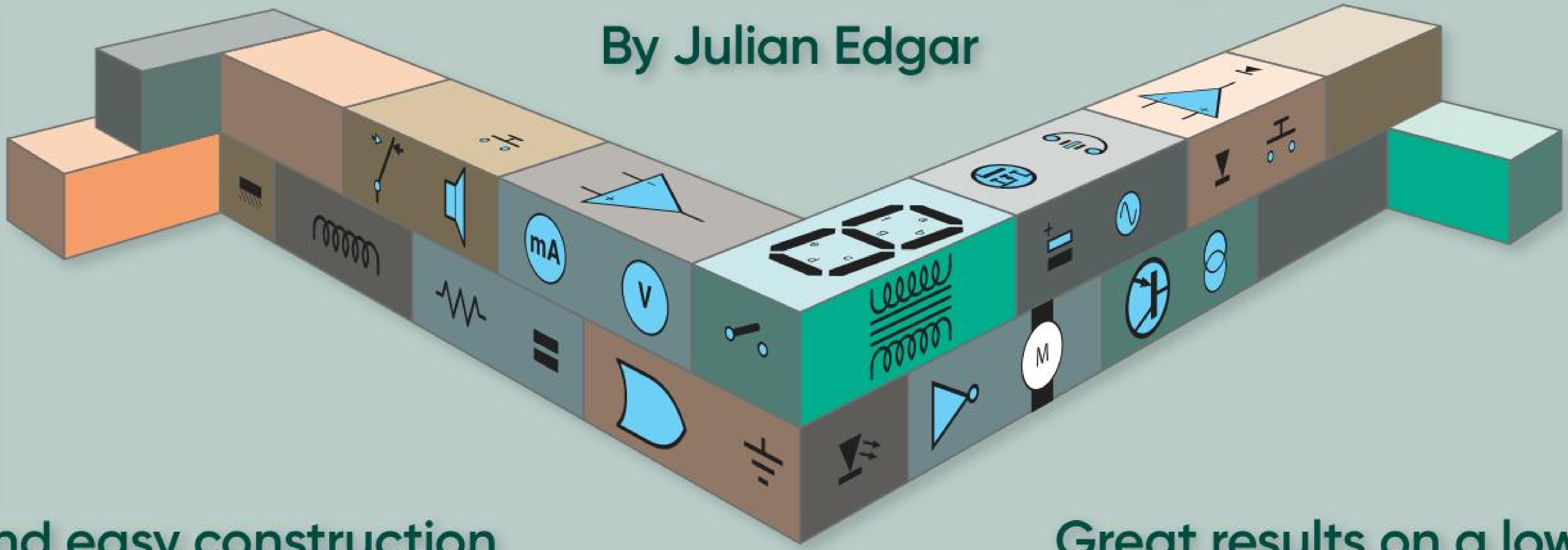
The Royer oscillator has a few undesirable characteristics. First, it tends to produce large simultaneous voltage and current spikes which may damage the transistors. Second, the frequency of oscillation is dependent on the supply voltage, which may be problematic in some designs. Third, the large spikes, and possible high frequency oscillations (not the main oscillations) after each switch event, can generate a lot of radio frequency interference (RFI). Adding an inductor between the centre tab of the primary and the supply can reduce the spikes and improve efficiency.

Baxandall oscillator

Before finishing our discussion it is worth taking a quick look at the circuit in Fig.9 (also an LTspice schematic). This circuit is frequently referred to as a Royer oscillator, but is also called the 'Baxandall oscillator' after Peter Baxandall, who published a paper on it in 1959. Many of the 'Royer' circuits in the CCFL step up converters mentioned at the start of the article are Baxandall oscillators. A different name is probably preferable as the operating principle is very different. Of particular relevance to the preceding discussion is that the transform does not saturate in the Baxandall oscillator. A key difference from the Royer circuit is the capacitor (C2) across the primary winding (L1-L2), which creates a resonant LC circuit and leads to sinewave oscillation, unlike the square wave for the Royer circuit. The LC resonant oscillator drives the alternate switching of the transistors via the feedback winding in a similar way to the Royer circuit. The transistor switching in turn sustains the resonant oscillation.

Simulation results for the Baxandall circuit are shown in Fig.10. The voltages at the two collectors (top two traces) are half sinewaves, but the voltage across the whole primary (L1-L2) is a full sinewave (bottom trace). The circuit in Fig.9 is not a suggested design, it is just a configuration that produced illustrative waveforms for a typical circuit of this type.

Electronic Building Blocks



By Julian Edgar

Quick and easy construction

Great results on a low budget

Electronic Stethoscope for Machinery

Here's a great beginner's project – easy and low cost to build and very useful in diagnosing all sorts of noises in machinery and cars.

The author listening to the fuel injectors on a diesel Mercedes. The electronic stethoscope will quickly show which injectors are working – and which are not. (Photo: Georgina Edgar)

If you work on machinery, you've probably come across a device like this – an amplified microphone that uses a steel probe. You touch the end of the probe to the part of the machine where you want to hear what is happening and then listen to the sounds on earphones. But the trouble is, commercial machinery stethoscope units start at about £50 – and go up rapidly from that price. On the other hand, this stethoscope is based around an eBay kit that will cost you only a few pounds – and the rest of the components that you need will probably already be in your spare parts collection or useful-to-keep junk box.

Starting point

The starting point for this project is a Banggood product (Fig.1) – dubbed in the company's idiosyncratic syntax-free style, 'DIY Electronic Kit Set Hearing Aid Audio Amplification Amplifier Practice Teaching Competition Electronic DIY Interest Making' (item ID 1607893). At the time of writing, it costs from £6.50 (approx US$9) including VAT and delivery to your door. Similar units are available from AliExpress, Amazon, eBay and the other usual online suspects, so shop around.

Assembly

The kit comprises a small PCB on which you build a simple three-transistor amplifier. A parts overlay diagram is provided and the PCB itself is solder-masked and well-labelled. Soldering the parts to the PCB will take you less than 20 minutes, but as always, use a multimeter/DVM to measure resistor values and mount the low-profile parts first. Always double-check components that must be mounted with the correct orientation – in this case, the electrolytic capacitors, the transistors and microphone. (Refer carefully to the overlay diagram for the microphone polarity.)

I suggest that when you build the kit, you mount the microphone, volume adjustment pot and switch well off the board. That way you can easily unsolder

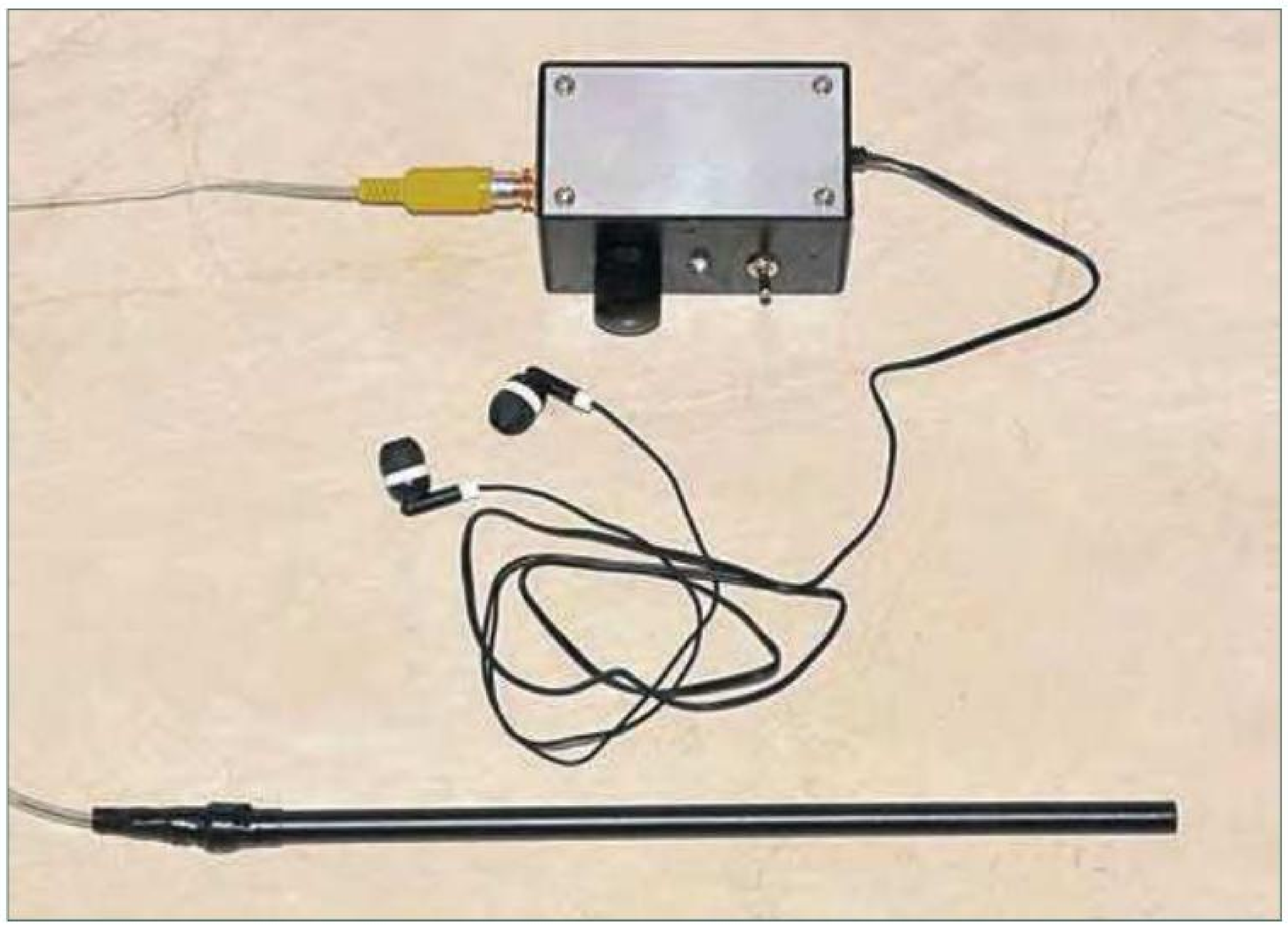


Fig.1. The amplifier – complete with volume control, LED power indicator and on/off switch – and the stethoscope probe and earphones. Detect and diagnose mechanical ailments with ease using this listening system!

(or cut off) these components later, but still initially complete the board and thus test that it works. (More on this in a moment.)

All the components are through-hole (oddly, except for the earphone socket – but that has large surface-mount pads so it's easy to solder) and while some parts are rather close together, this isn't a kit that will cause any issues, even if you're not an experienced 'solderer'.

In addition to the PCB and on-board components, with the purchase you also get the earphones and a 3V CR2032 button cell – amazing value for a few quid, delivered!

Testing, testing... 1, 2, 3

Once you have built the kit, test that it works. Turn the on-board pot fully anti-clockwise, switch on power (there's a small switch on the PCB), plug in the earphones and listen. Then, gradually wind the pot clockwise. You should hear a startling array of sounds that you were not aware of when listening normally. The quality and sensitivity of the amplifier are both very good – you'll probably be able to literally hear yourself breathing.

Now, put it in a box

Once you've ensured everything is working (and if it isn't, check all component orientations and look for solder bridges or bad solder connections), you can take a few steps backwards. Backwards? Well, because we want to mount the board in a box; plus, a new switch, pot and microphone socket will be needed. Any box will do – the only requirements are that everything will fit inside it, and it's suitably durable. As a guide, I used a 'jiffy' box that was 85 x 55 x 35mm.

Remove the pot, switch and microphone from the PCB. You won't be using the pot and switch again, but you will be re-using the microphone, so take care in removing this part.

You'll now need a 10kΩ pot, a suitable knob for it, an SPST switch (single-pole, single-throw – ie, a normal on/off switch), and some type of plug and socket for the microphone cable. I used an RCA socket and plug for the microphone, but that's just because I had them handy. (Technically, you should probably use a shielded cable for the microphone, and a suitable plug/socket combination that continues the shield, but it's probably not that important unless you will be using the electronic stethoscope in very electrically noisy environments.)

Working one component at a time, you can now remote mount the switch, pot and microphone. If you're unsure how to do this, look at the pin-outs on the board. The pot, for example, has three connections. Orient your new pot in the same way as the original one was wired – you can now see that there are two 'end' pins and a central pin (aka the 'wiper', sometimes marked 'w'). Connect the new pot in just the same way – left-hand pin on the board to left-hand pin on the new pot, centre pin to centre pin, and right-hand pin to right-hand pin. Now do the same for the power switch and microphone socket. You want to use leads that are long enough that these can all be mounted in the walls of the box but still connect to the PCB.

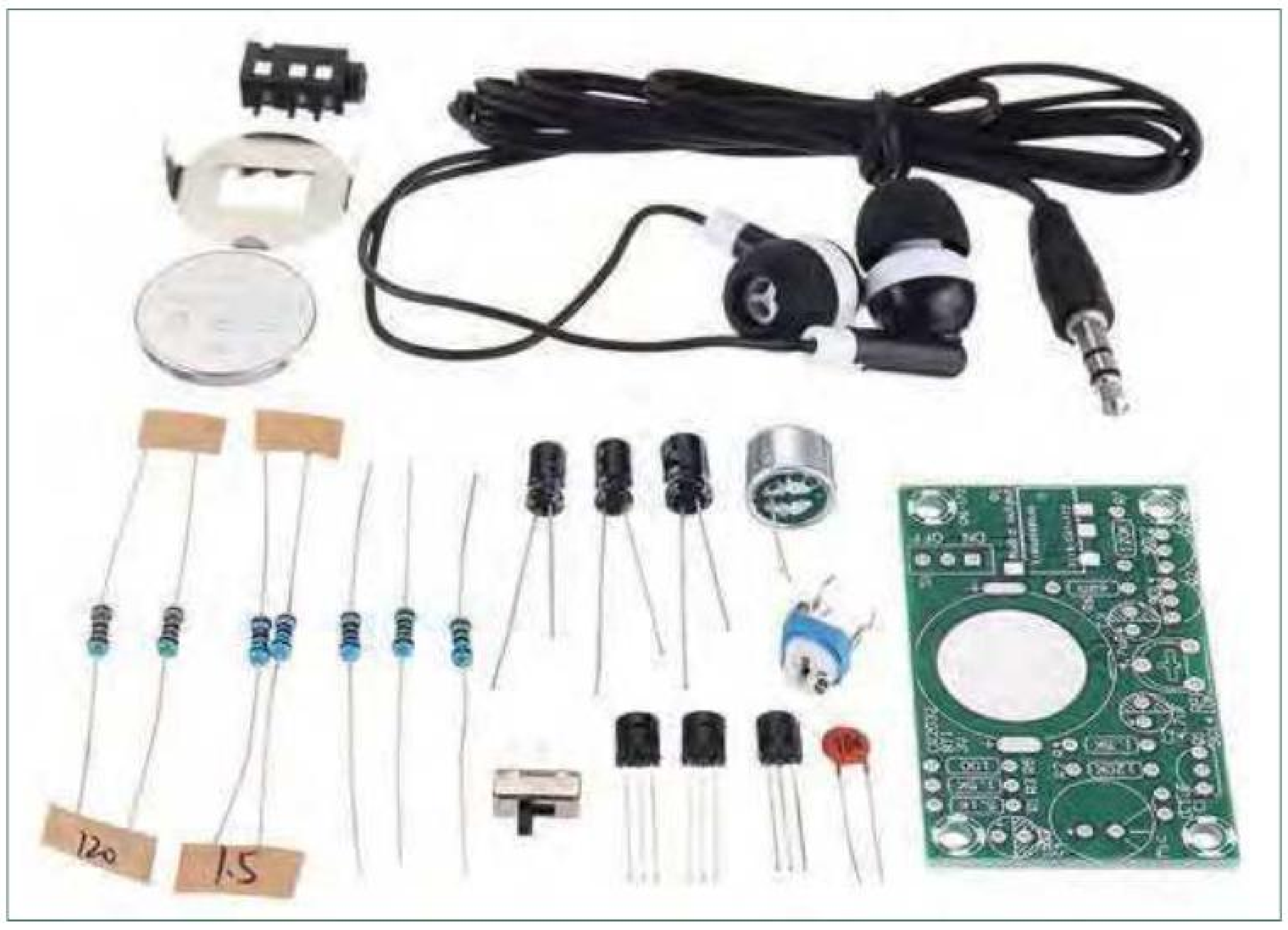


Fig.2. The Banggood kit includes the PCB, electronic components, button cell and earphones. You need to add only a few low-cost components to produce an effective and easy-to-use electronic stethoscope. (Courtesy Banggood)

Connecting the microphone

After the power switch, level pot and microphone input have all been connected on flying leads, it's time to remote-mount the microphone. You can decide on how long you want this wire to be – I used a figure-8 cable length of about 80cm. Solder the plug that you are using to this lead and then connect the microphone, ensuring you maintain correct polarity. (If the lead doesn't have a trace to indicate which conductor is which, use your DVM/multimeter, set to the continuity function, to work it out.) Insulate the microphone connections – you don't want them touching each other or anything else.

You should now be able to power-up the board again and check that the amplifier still works as it did before.

When you are happy that all the wiring has been completed properly, drill appropriate holes in the box and install the components. In most cases, the pot and switch will install from within the box, so none of your new wiring needs to be broken. However, many sockets insert from outside so you may need to unsolder the socket connections, insert the socket and then resolder these connections. Now drill a hole in the box

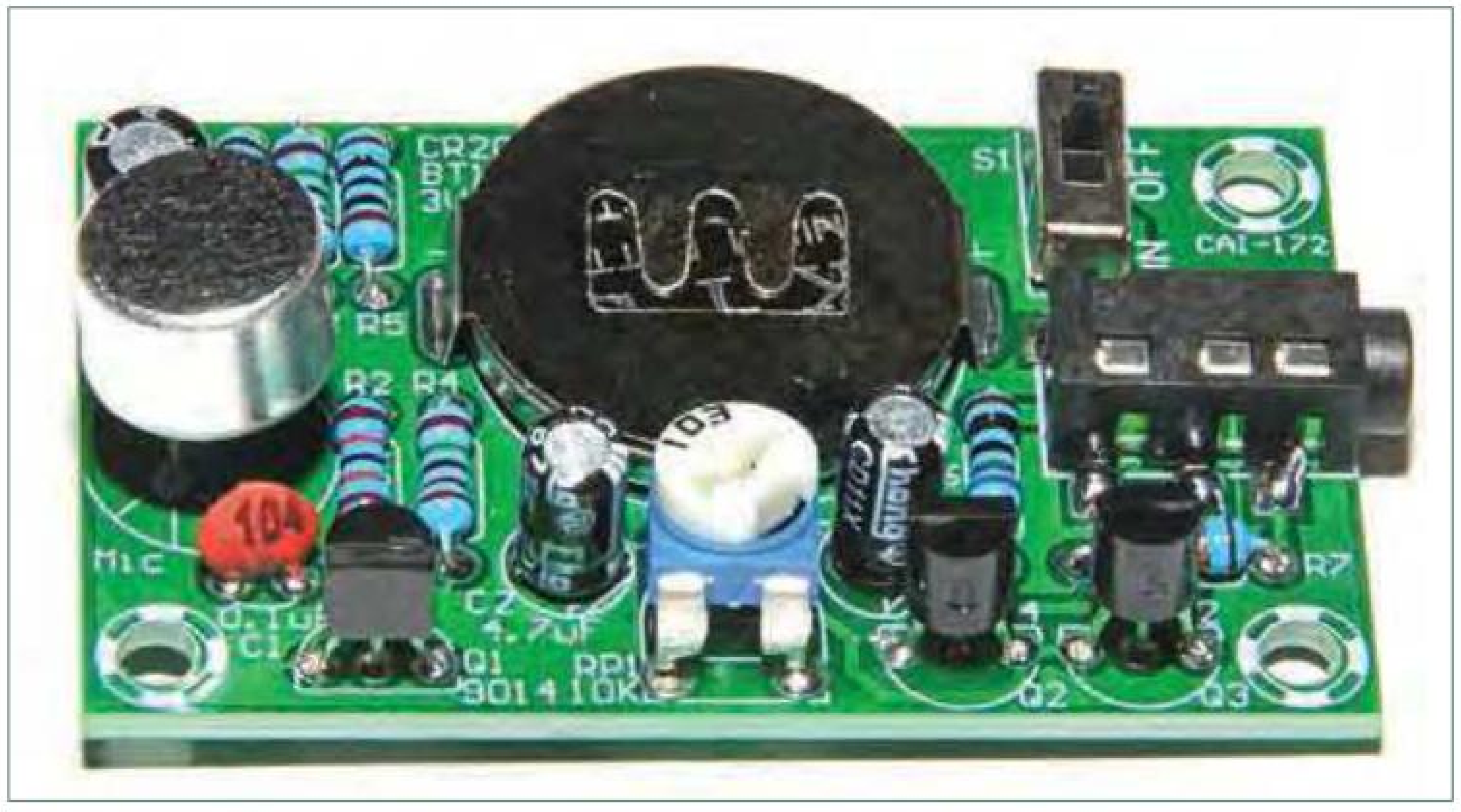


Fig.3. The completed kit. Note the CR2032 button cell in its holder – it's provided with the kit. The current drain of the circuit is fairly high, so if you expect to use the stethoscope for long periods, you may wish to replace the button cell with two AA cells (and holder) to provide longer battery life. However, for normal short periods of use, the button cell is fine.

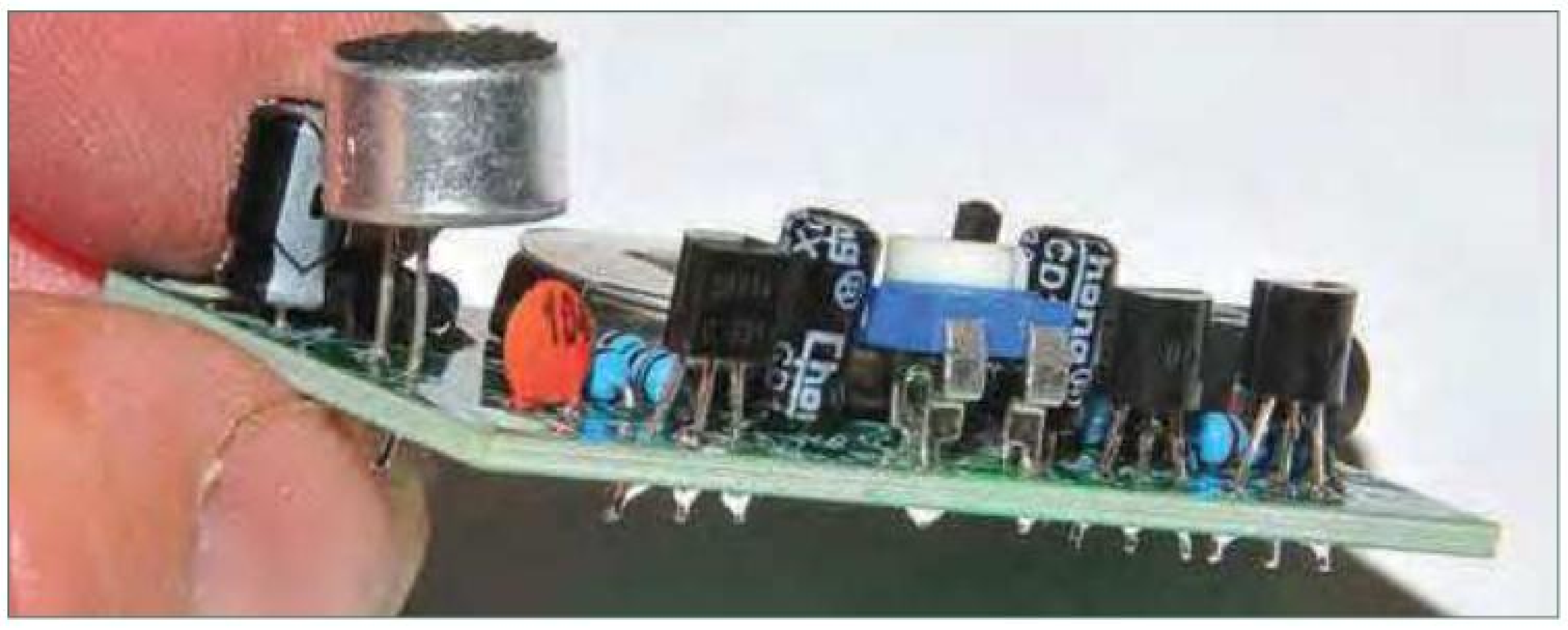


Fig.4. The pot, microphone and switch should be mounted well off the PCB, allowing their easy removal after initial testing. The microphone is subsequently mounted remotely, while the switch and pot are replaced with new items that are wired to flying leads, allowing them to be mounted in the walls of the box.

wall for the on-board earphone socket – position the hole so that the plug can be inserted from outside the box.

The stethoscope probe

You may be wondering why we used a plug and socket for the microphone, rather than just extending the cable through the box. The reason is that it's useful to be able to fit microphones with different mechanical connections. (The kit comes with only one microphone, but these electret microphone inserts are readily and cheaply available.) For example, you can have one microphone mounted on the end of a metal rod for 'probing' duties, and another mounted on a battery clip to be attached remotely to normally inaccessible machinery parts. Simply plug in the microphone you want to use to match the test.

Irrespective of the mechanical connection you want to make, the microphone needs to be firmly mounted. That mounting approach is up to you – previously, I have glued microphones to battery clips (it worked very well) but with the system shown here, I taped the microphone to the end of a 20cm steel rod. In all cases, ensure that the microphone's electrical connections are protected against strain and bending – these connections can be quite fragile.

In use

To use the stethoscope, place the end of the probe against the part of the machinery that's of interest. Start with the volume control at its lowest and after switching on power, slowly turn up the volume until the listening level is comfortable. For example, to determine in a car engine that all injectors are running, place the tip of the probe against each injector in turn. You will easily be able to hear the clicking of the injector above other engine noises. Other uses include detecting worn ball and roller bearings, plain bearings with excessive clearances, and even vacuum and compressed air leaks.

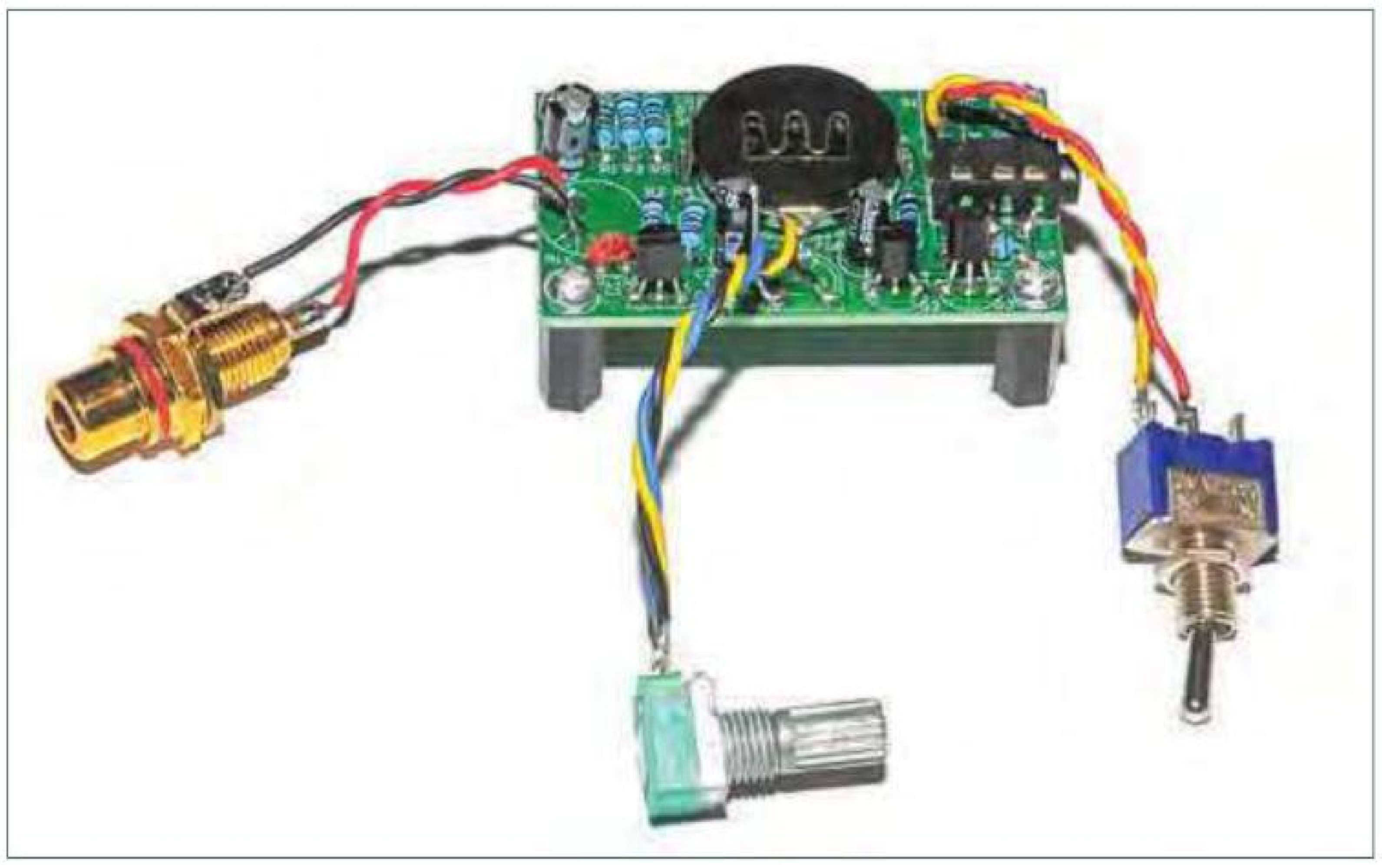


Fig.5. The socket for the microphone, the new pot and switch wired into place before the assembly is mounted in the box. These components (and the PCB stand-offs and screws) are supplied by the builder – they're not in the kit.

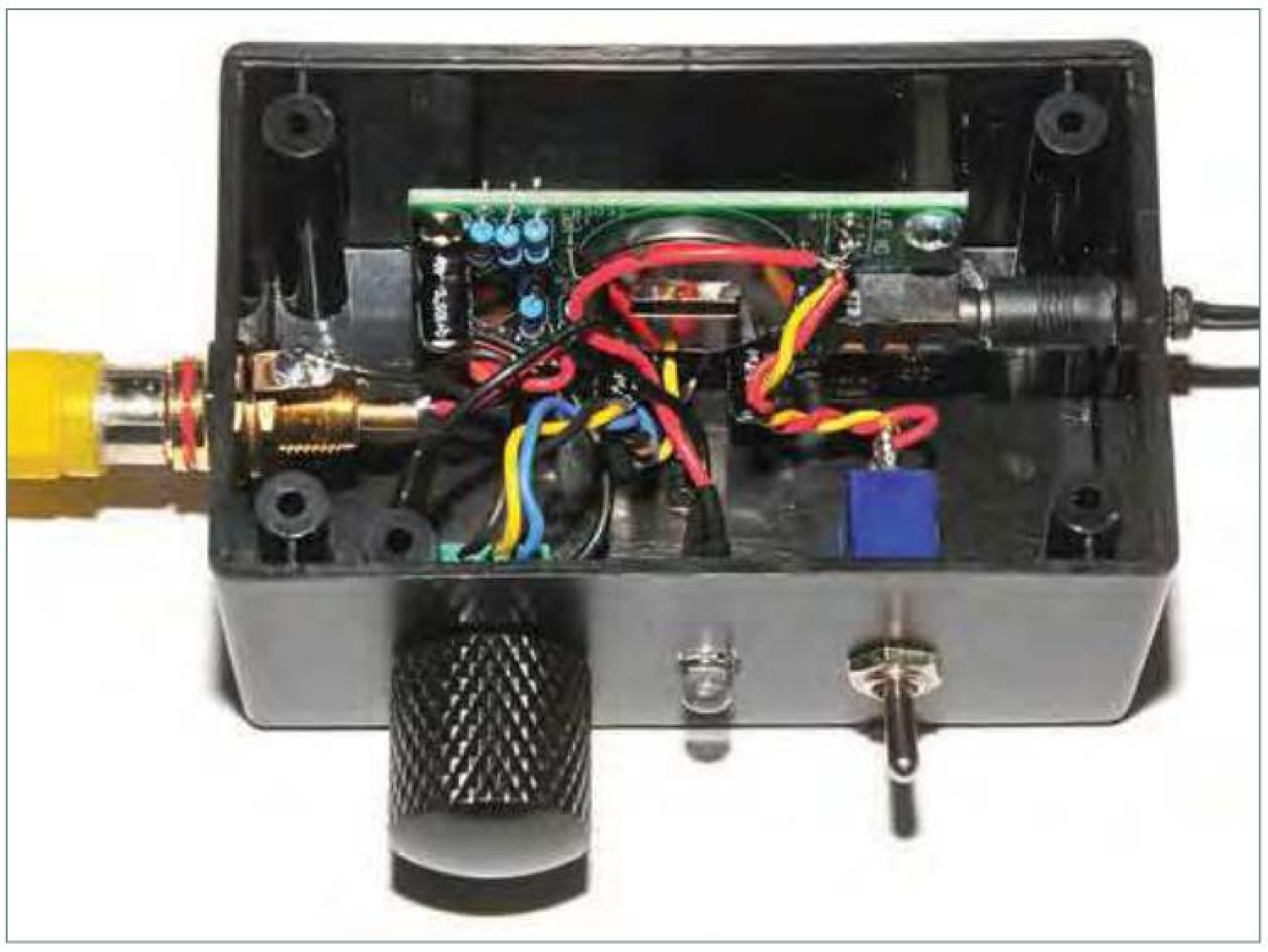


Fig.6. The assembled electronic stethoscope, minus the sensing probe. Orient the PCB so that the button cell can be replaced – that is, have the opening in the holder pointing upwards. Here the optional power LED can be seen between the volume adjustment pot and the on/off switch. Finally, note how a hole has been placed in the side of the box to allow the earphones to be plugged into the PCB socket.

Power LED?

A nice-to-have little extra is a power indicator. If you want to show visually that the stethoscope is switched on, you can add a power LED. You don't want this drawing much current, and one easy approach is to use an LED pre-wired for 12V. (The current that then flows at 3V is very small, but modern LEDs are still quite visible at this voltage.)

But where do you connect this LED? If you look at the circuit diagram, you can see that when the switch is closed, battery voltage can be picked up on one side of the switch, and ground is easiest obtained from one side of the microphone. Carefully use your multimeter/DVM and measure between these connections to ensure you can see battery voltage when the stethoscope is switched on. Then solder the LED in place.

If you don't have any of these '12V' LEDs available, I suggest you buy a bunch – they're very useful in all sorts of applications and come with appropriate current-limiting and a useful length of cable. At the time of writing, eBay item 353817519631 offers 50 pieces (white, red, yellow, green and blue) delivered for under £10. I also like the ones that have a little extra circuity built in and can flash all sorts of weird patterns – search eBay for '12V led prewired flashing' – for example, eBay item 154761929698.

Remember that the LED is polarised – typically with these pre-wired LEDs, red is positive and black negative (ground), so connection is straightforward.

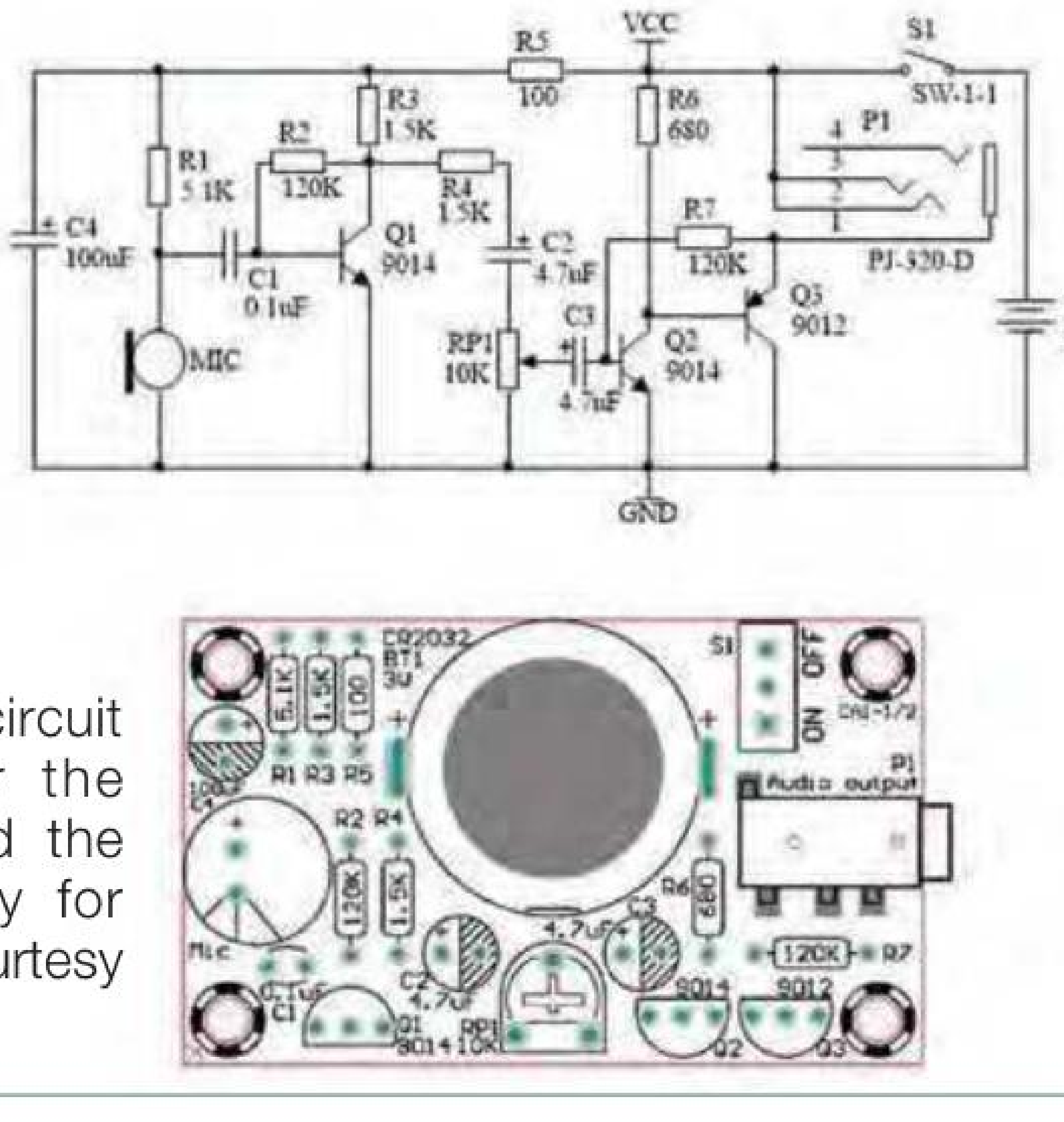


Fig.7. The circuit diagram for the amplifier and the parts overlay for the PCB. (Courtesy Banggood)

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0
1
2
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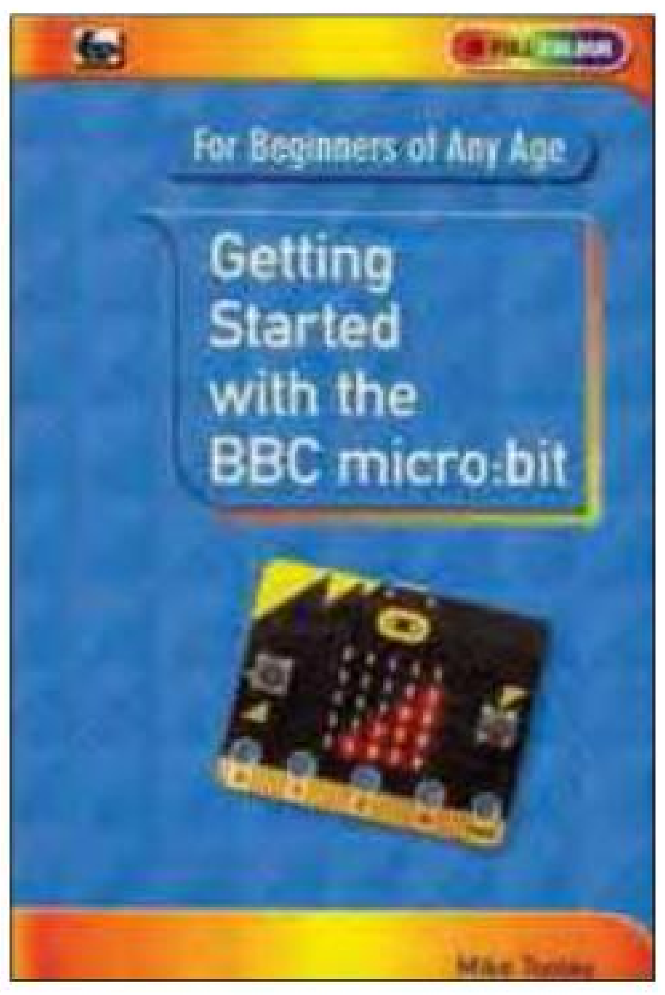

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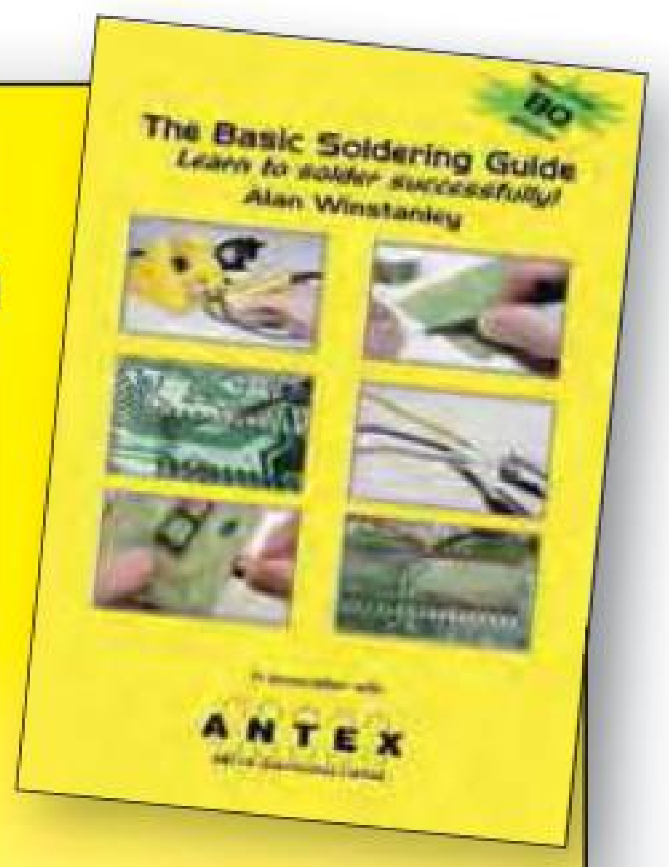

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JULY 2019

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For editorial contact details see page 7.

Next Month – in the June issue

8-pin / 14-pin / 20-pin PIC Programming Helper

It's incredible what you can achieve with an 8-pin microcontroller. However, programming and debugging these chips can be a challenge due to the need to use the programming and reset pins for other purposes. This little board makes working with these (and some larger) PICs much easier!

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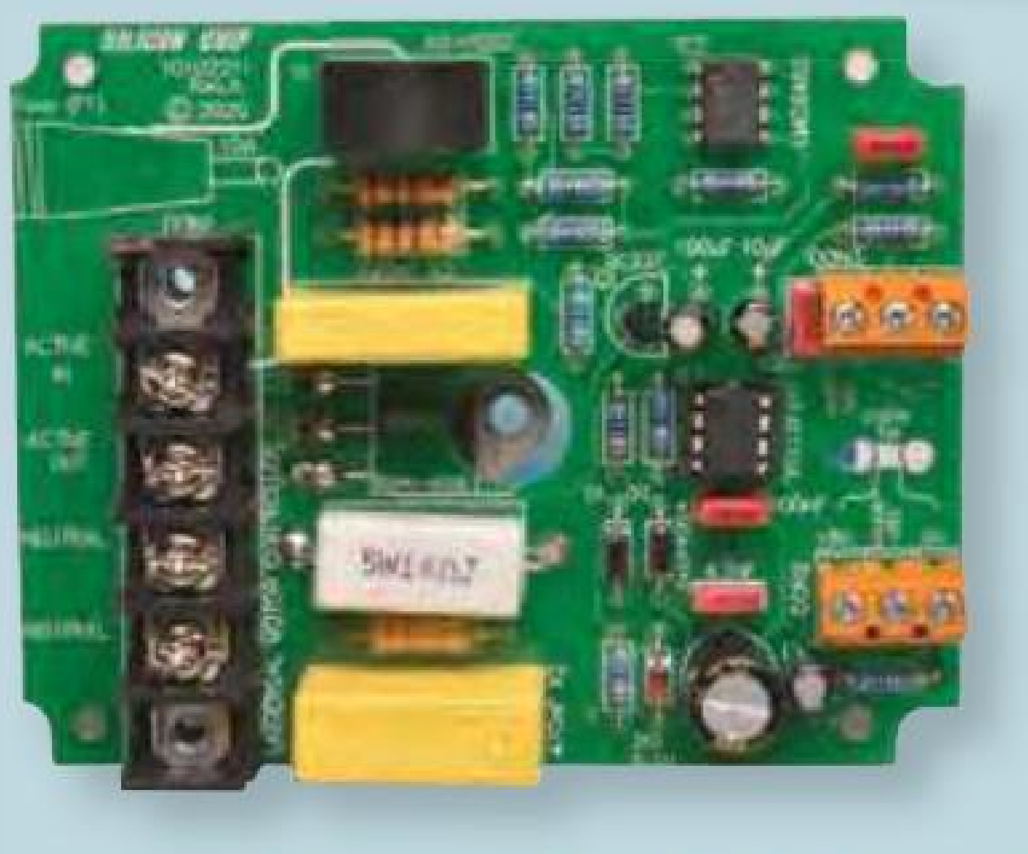

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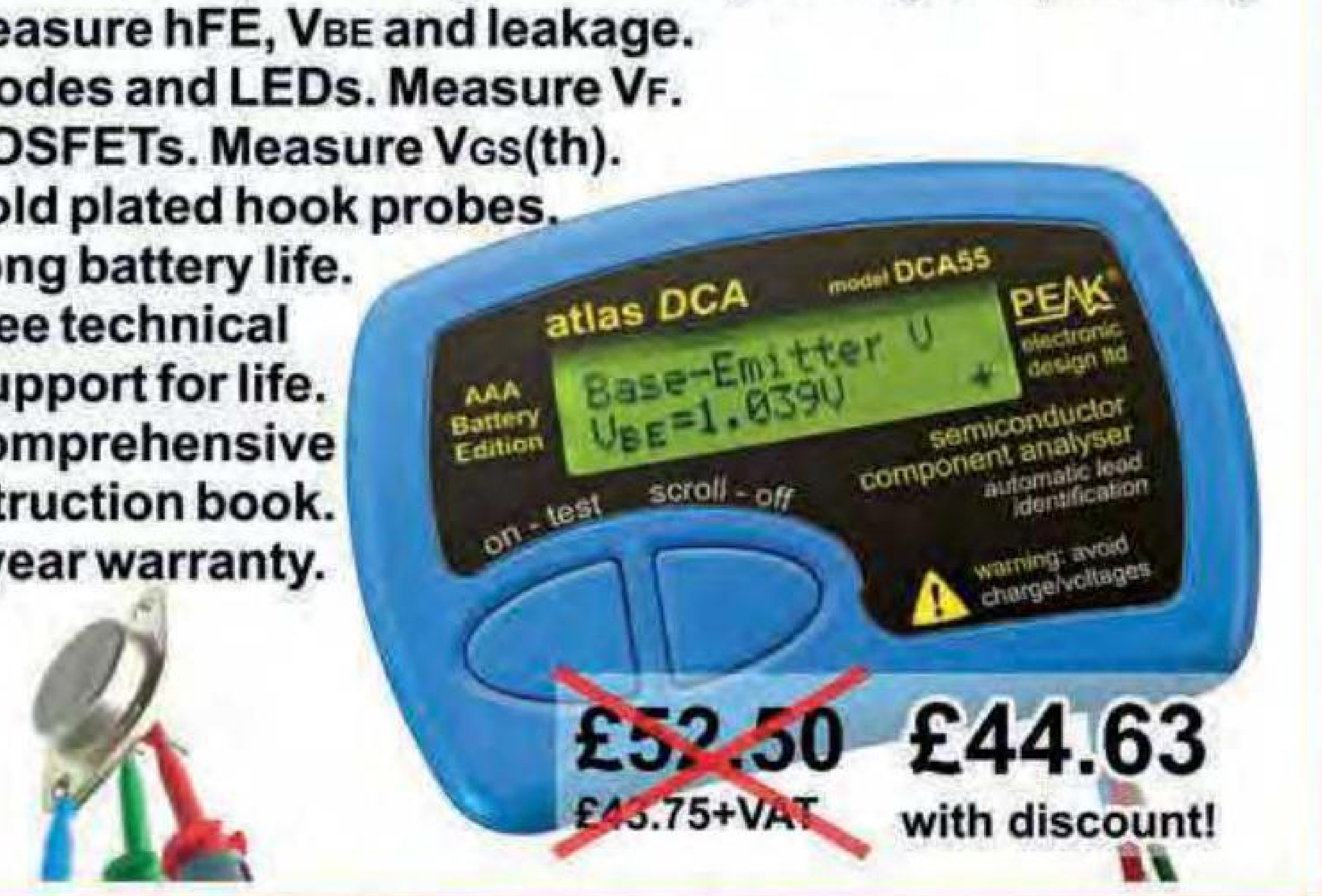
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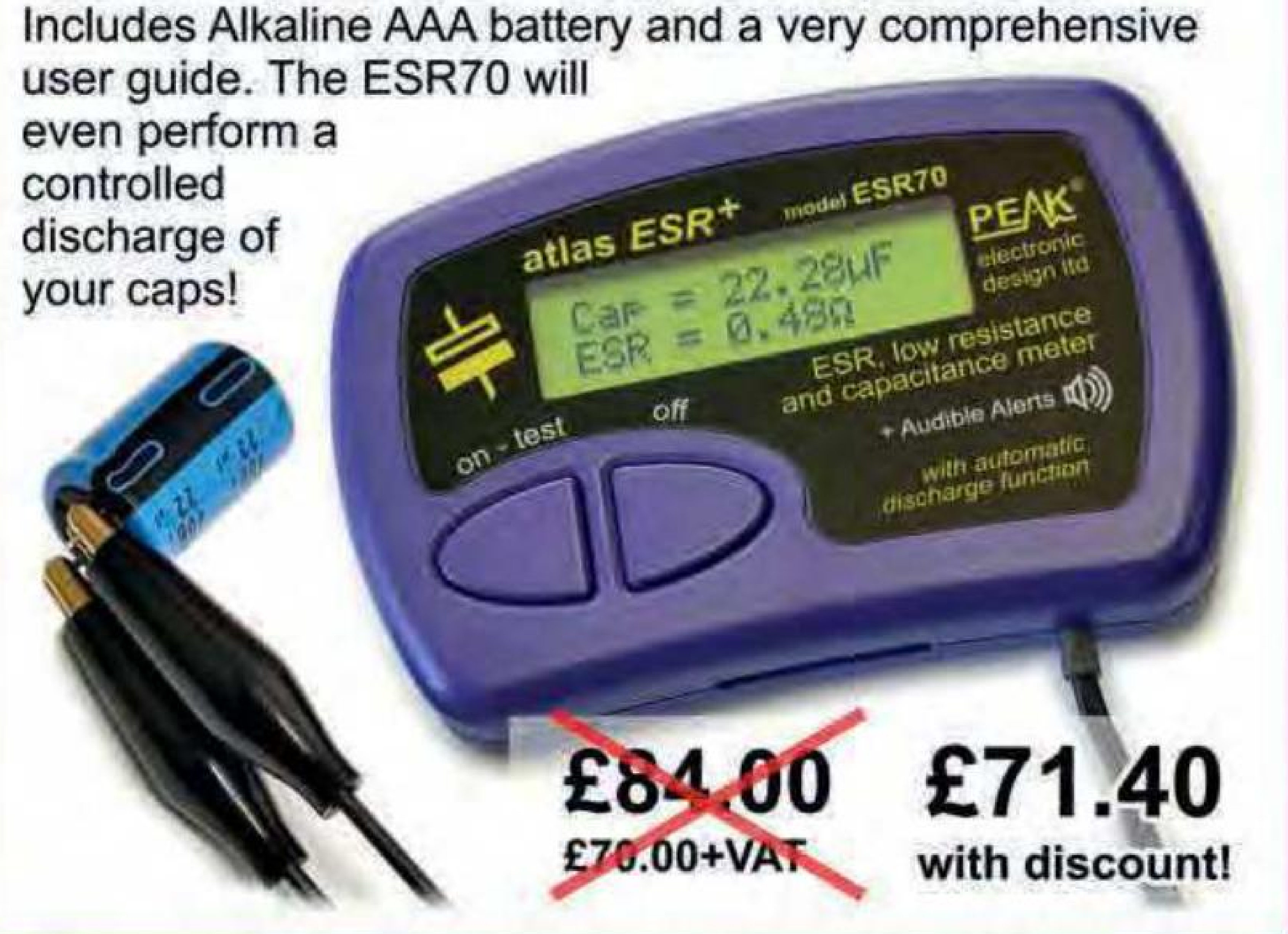
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